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SECTION 20

MOTORS AND DRIVES

Former contributors: Kenneth C. Cornelius, John H. Dulas, Alexander Kusko, Kelly A. Shaw, and Syed M. Peeran.

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20.1 GENERAL

Types of Electric Motors. Electric motors provide motive power to a wide variety of domestic and industrial machinery. Their versatility, reliability, and economy cannot be equaled by any other form of drive. Successful motor application depends on selecting a type of motor which satisfies the kinetic starting, running, and stopping requirements of the driven machinery. There are several methods of classifying electric motors. First, based on the electric power supply, motors are classified as dc and ac motors. Figure 20-1 shows further classification of ac and dc motors based upon the stator and rotor construction.

Classifications based upon size and applications are micro, fractional-horsepower, integral-horsepower, gear, torque, servo, and stepper motors in both standard and premium efficiency designs. Various types of enclosures have been standardized by the National Electric Manufacturers Association, U.S.A. (NEMA). The following are the standard enclosure types and their characteristics:

Types	Characteristics
Open:	
Dripproof	Operate with dripping liquids up to 15°C from vertical
Splashproof	Operate with splashing liquids up to 100°C from vertical
Guarded	Guarded by limited size openings (less than $\frac{3}{4}$ in)
Semiguarded	Only top half of motor guarded
Dripproof fully guarded	Dripproof motor with limited-size openings
Externally ventilated	Ventilated with separate motor-driven blower; can have other types of protection
Pipe ventilated	Openings accept inlet ducts or pipe for air cooling
Weather-protected type 1	Ventilating passages minimize entrance of rain, snow, and airborne particles; passages are less than $\frac{3}{4}$ in. in diameter
Weather-protected type 2	Motors have, in addition to type 1, passages to discharge high-velocity particles blown into the motor
Totally enclosed:	
Nonventilated (TENV)	Not equipped for external cooling
Fan-cooled (TEFC)	Cooled by external integral fan
Explosionproof	Withstands internal gas explosion; prevents ignition of external gas
Dust-ignitionproof	Excludes ignitable amounts of dust and amounts of dust that would degrade performance
Waterproof	Excludes leakage except around shaft
Pipe-ventilated	Openings accept inlet ducts or pipe for air cooling
Water-cooled	Cooled by circulating water
Water-and-air-cooled	Cooled by water-cooled air
Air-to-air-cooled	Cooled by air-cooled air
Guarded TEFC	Fan-cooled and guarded by limited-size openings
Encapsulated	Has resin-filled windings for severe operating conditions

NEMA classification according to the variability of speed includes constant-speed motors such as ac synchronous motors; induction motors with low, medium, or high slip; dc short-wound motors; varying-speed motors such as dc series motors or repulsion motors; and variable-speed motors such as dc shunt-, series-, and compound-wound motors.

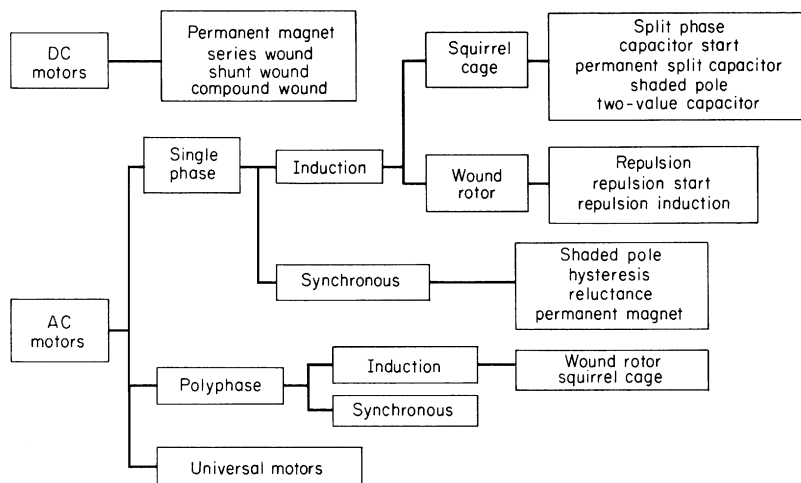


FIGURE 20-1 Classification of ac and dc motors.

Standards. Motors and generators are required to meet various industry and national standards and in some instances specific local codes and customer specifications. The more important of these standards may be briefly described as follows:

1. *NEMA Standards* are voluntary standards of the National Electrical Manufacturers Association and represent general practice in the industry. They define a product, process, or procedure with reference to nomenclature composition, construction, dimensions, tolerances, operating characteristics, performance, quality, rating, and testing. Specifically, they cover such matters as frame sizes, torque classifications, and basis of rating.
2. *IEEE Standards (AIEE)* concern fundamentals such as basic standards for temperature rise, rating methods, classification of insulating materials, and test codes.
3. *USA Standards* are national standards established by the United States of America Standards Institute, which represents manufacturers, distributors, consumers, and others concerned. USA Standards may be sponsored by any responsible body and may become national standards only if a consensus of those having substantial interest is reached. Standards may cover a wide variety of subjects such as dimensions, specifications of materials, methods of test, performance, and definition of terms. USA Standards frequently are those previously adopted by and sponsored by NEMA, IEEE, etc. The chief motor and generator standard of USASI is C50, "Rotating Machinery," which is substantially in agreement with current NEMA Standards.
4. *National Electrical Code* is a USA Standard sponsored by the National Fire Protection Association for the purpose of safeguarding persons and buildings from electrical hazards arising from the use of electricity for light, heat, power, and other purposes. It covers wiring methods and materials, protection of branch circuits, motors and control, grounding, and recommendations, regarding suitable equipment for each classification.
5. *Underwriters' Laboratories, Inc.* is an independent testing organization, which examines and tests devices, systems, and materials with particular reference to life, fire, and casualty hazards. It develops standards for motor and control for hazardous locations through cooperation with manufacturers. It has several different services by which a manufacturer can indicate compliance with Underwriters' Laboratories Standards. Such services are utilized on motors only in the case of explosionproof and dust-ignitionproof motors where label service is used to indicate to code-enforcing authorities that motors have been inspected to determine their adherence to Underwriters' Laboratories Standards for motors for hazardous locations.
6. *Federal Specification CC-M-641* for integral-horsepower ac motors has been issued by the federal government to cover standard motors for general government uses. Standard motors meet these specifications, but other Federal Specifications issued by various branches of the government for specific use may require special designs.
7. *World Standards.* Standards similar to our NEMA Standards have been established in other countries. The most significant are
 - a. IEC (International Electrochemical Commission) Standard 72-1, Part 1
 - b. German Standard DIN 42673
 - c. British Standard BSI-2960, Part 2

These standards specify dimensions, classes of insulation, and in some cases horsepower ratings.

20.2 DIRECT-CURRENT MOTORS

Classes of DC Motors. Direct-current motors are used in a wide variety of industrial applications because of the ease with which the speed can be controlled. The speed-torque characteristic may be varied to almost any useful form. Continuous operation over a speed range of 8:1 is possible. While ac motors tend to stall, dc motors can deliver over 5 times the rated torque (power supply permitting).

Reversal is possible without power switching. Permanent-magnet motors are available in fractional-horsepower ratings, while wound-field dc motors are classified as (1) shunt motor, in which the field winding is connected in parallel with the armature; (2) series motor, in which the field winding is connected in series with the armature; and (3) compound motor, which has a series-field and shunt-field winding. The shunt motor is used in constant-speed applications such as drives for dc generators in dc motor-generator sets. The series motor is used in applications where a high starting torque is required, such as in electric traction, cranes, and hoists. In compound motors, the droop of the speed-torque characteristic may be adjusted to suit the load.

The construction of dc motors with a wound field is practically identical to that of dc generators; with minor adjustment, the same dc machine may be operated either as a dc generator or as a motor. (See Sec. 8 of this handbook for construction, armature windings, commutator, etc.)

Permanent-magnet dc motors have fields supplied by permanent magnets that create two or more poles in the armature by passing magnetic flux through it. The magnetic flux causes the current-carrying armature conductors to create a torque. This flux remains basically constant at all motor speeds—the speed-torque and current-torque curves are linear.

Shunt Motors. DC shunt motors are suitable for application where constant speed is needed at any control setting or where appreciable speed range (by field control) is needed. The field circuit connection is shown in Fig. 20-2a.

Since a motor armature revolves in a magnetic field, an emf is generated in the conductors which is opposed to the direction of the current and is called the counter emf. The applied emf must be large enough to overcome the counter emf and also to send the armature current I_a through R_m , the resistance of the armature winding, the brushes; or

$$E_a = E_b + I_a R_m \quad \text{volts} \quad (20-1)$$

where E_a = applied emf and E_b = counter emf. Since the counter emf at zero speed, that is, at starting, is identically zero and since normally the armature resistance is small, it is obvious in view of Eq. (20-1) that, unless measures are taken to reduce the applied voltage, excessive current will circulate in the motor during starting. Normally, starting devices consisting of variable series resistors are used to limit the starting current of motors.

The torque of a motor is proportional to the number of conductors on the armature, the current per conductor, and the total flux in the machine. The formula for torque is

$$\text{Torque} = 0.1175 Z \phi I_a \frac{\text{poles}}{\text{paths}} \times 10^{-8} \text{ lb} \cdot \text{ft} \quad (20-2)$$

where Z = total number of armature conductors, ϕ = total flux per pole, and I_a = armature current taken from the line.

$$E_b = E_a - I_a R_m = Z \phi \frac{\text{r/min}}{60} \frac{\text{poles}}{\text{paths}} \times 10^{-8} \quad \text{volts} \quad (20-3)$$

$$\text{or} \quad \text{r/min} = 60 \frac{E_a - I_a R_m}{Z \phi} \frac{\text{paths}}{\text{poles}} \times 10^8 \quad (20-4)$$

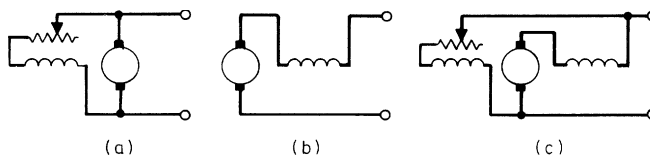


FIGURE 20-2 Field circuit connections of dc motor.

For a given motor, the number of armature conductors Z , the number of poles, and the number of armature paths are constant. The torque can therefore be expressed as

$$\text{Torque} = \text{constant} \times \phi I_a \quad (20-5)$$

and the speed, likewise, is expressed as

$$\text{Speed} = \text{constant} \times (E_a - I_a R_m) / \phi \quad (20-6)$$

In the case of the shunt motor, E_a , R_m , and ϕ are constant, and the speed and torque curves are shown as curves 1 (Fig. 20-3); the effective torque is less than that generated by the torque required for the windage and the bearing and brush friction. The drop in speed from no load to full load seldom exceeds 5%; indeed, since ϕ , the flux per pole, decreases with increase of load, owing to armature reaction, the speed may remain approximately constant up to full load.

Speed and Torque of Series Motors. Equations (20-6) and (20-5) apply to motors of all continuous-current types. In the case of series motors, the flux ϕ increases with the armature current I_a ; the torque would be proportional to I_a^2 were it not that the magnetic circuit becomes saturated with increase of current. Since ϕ increases with load, the speed drops as the load increases. The speed and torque characteristics are shown in curves 3 (Fig. 20-3).

If the load on a series motor becomes small, the speed becomes very high, so that a series motor should always be geared or direct-connected to the load. If it were belted and the belt were to break, the motor would run away and would probably burst.

For a given load, and therefore for a given current, the speed of a series motor can be increased by shunting the series winding or by short-circuiting some of the series turns so as to reduce the flux. The speed can be decreased by inserting resistance in series with the armature.

Compound Motors. Compound-motor connections are shown in Fig. 20-2c. The compound motor is a compromise between the shunt and the series motors. Because of the series winding, which assists the shunt winding, the flux per pole increases with the load, so that the torque increases more rapidly and the speed decreases more rapidly than if the series winding were not connected; but the motor cannot run away under light loads, because of the shunt excitation. The speed and torque characteristics for such a machine are shown in curves 2 (Fig. 20-3).

The speed of a compound motor can be adjusted by armature and field rheostats, just as in the shunt machine.

Indirect compound is used on some dc motors. In this case, the heavy strap-wound series field is replaced by a wire-wound field similar to a small shunt field. This field is excited by an unsaturated dc exciter, usually separately driven at constant speed. This exciter is excited by the line current of the motor for which it supplies the series excitation (see Fig. 20-4). The output voltage and the current from the exciter are proportional to the main motor current; so a given proportionality exists between the load current of the motor and its wire-wound series-field strength. The use of a reversing switch and rheostat in the armature circuit of the series exciter permits variations in strength and even polarity

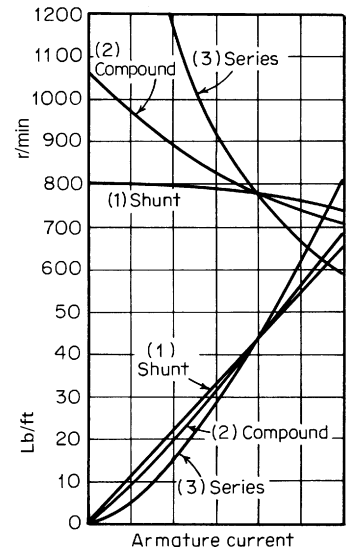


FIGURE 20-3 Motor characteristics.

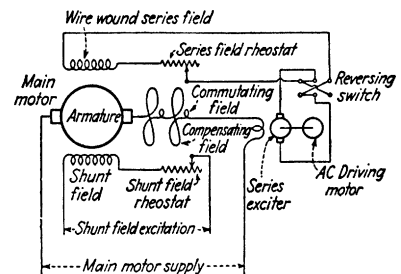


FIGURE 20-4 Direct-current motor with indirect compounding using a series exciter.

of the series field. This furnishes an easy method of changing the compounding of the motor if desired for various speeds, to maintain constant-speed regulation over a speed range. If desired, the series exciter rheostat can be mechanically connected to the shunt-field rheostat to accomplish this automatically.

Power Supplies. Power supplies to dc motors may be batteries, a dc generator, or rectifiers. The permanent-magnet and miniature motors use battery power supplies. Large integral-horsepower dc motors such as rolling-mill motors use dc generators as the power supply. Most fractional-horsepower and integral-horsepower dc motors operate with rectifier power supplies. Some of the types of rectifier power supplies are as follows:

1. Single-phase, half-wave
2. Single-phase, half-wave, back rectifier
3. Single-phase, half-wave, alternating-current voltage controlled
4. Single-phase, full-wave, firing angle controlled
5. Single-phase, full-wave, firing angle controlled, back rectifier
6. Three-phase, half-wave, voltage controlled
7. Three-phase, half-wave, firing angle controlled

The NEMA standard letter designations of dc motor test power supplies are as follows:

Power supply A—dc generator

Power supply C—3-phase 6-pulse controlled rectifier (230 V L-L, 60 Hz)

Power supply D—3-phase 6-pulse controlled rectifier (with three thyristors and three diodes) with free-wheeling diode (230/460 V L-L, 60 Hz)

Power supply E—3-phase 3-pulse controlled rectifier (460 V L-L, 60 Hz)

Power supply K—1-phase full-wave controlled rectifier with free-wheeling diode (230/115 V, 60 Hz)

When a direct-current integral-horsepower motor is operated from a rectified alternating-current supply, its performance may differ materially from that of the same motor when operated from a low-ripple direct-current source of supply, such as a generator or a battery. The pulsating voltage and current waveforms may increase temperature rise and noise and adversely affect commutation and efficiency. Because of these effects, direct-current motors must be designed or specially selected to operate on the particular type of rectified supply to be used. Armature-current form factor and ripple are two important parameters to be specified for motors which are required to operate with rectifier power supplies. The *form factor* is defined as the ratio of the rms value to the average value of the armature currents. Recommended rated form factors vary from 2.0 for 1-phase half-wave rectifier supplies to 1.1 for 3-phase full-wave rectifier supplies (see NEMA MG1-14.60). Because the letters used to identify the power supplies in common use have been chosen in alphabetical order of increasing magnitude of ripple current, a motor rated on the basis of one of these power supplies may be used on any power supply designed by a lower letter of the alphabet. For example, a motor rated on the basis of an E power supply may be used on a C or D power supply.

DC Motor Ratings. NEMA standard ratings of industrial dc motors for 240-V and 500/550-V dc supply voltages are given in Tables 10-4 and 10-5 of NEMA standard MG1. The rating is continuous unless otherwise specified. All short-term load tests shall commence only when the windings and other parts of the machine are within 5°C of the ambient temperature at the time of starting the test. Continuous and short-term ratings are based upon maximum ambient temperature and insulation class. Except in engine and boiler rooms, the maximum ambient temperature is 40°C and the insulation classes are A, B, and F, rated for temperature rises of 70°C, 100°C, and 130°C, respectively.

Losses and Efficiency. Power losses in dc motors are due to bearing friction, brush friction, windage, eddy currents and hysteresis in the armature core and pole faces, brush contact-drop, I^2R losses in the armature and field windings, and stray load losses. Typical values of total losses in industrial motors are 4% to 10% of the output. The bearing friction and brush friction losses are proportional to the speed of the motor, while the windage loss is proportional to the square of the speed. Eddy current loss in the armature teeth and in the armature core is proportional to the square of the speed and to the square of the air-gap flux density. Hysteresis loss in the armature teeth and core is proportional to the speed and the square of the flux density in the air gap. Brush contact drop is typically 1 V per brush arm for carbon-graphite brushes and 0.25 V for metal-graphite. Stray load losses are due to eddy currents in armature conductors, brush short-circuit losses in the commutator, and additional core loss arising from distortion of the magnetic field due to armature reaction. The efficiency of the dc motor is defined as

$$\eta = (\text{input electric power} - \text{losses}) / \text{input power} \times 100\% \quad (20-7)$$

Typical efficiency variation with output is shown in Fig. 20-5.

Short-Time Ratings. The effect of time and enclosure on motor rating may be seen from the following: A given frame will have a rating of 12 hp at 500 r/min as an enclosed machine on continuous duty, or 19 hp at 500 r/min as an open machine on continuous duty, or 31 hp at 500 r/min with a 1-h rating, or 40 hp at 500 r/min with a $\frac{1}{2}$ -h rating. The temperature rise on full load is 40°C as an open machine and 50°C as an enclosed machine. The horsepower is proportional to the speed over a range of 30% above or below the rated speed.

Methods of Speed Control. Speed of a dc motor is controlled either by varying the voltage across the armature, the field winding, or both. Series-parallel combinations are an effective means of reducing armature voltage and motor speed. This method is applied in cam-controlled traction motors. Two identical motors are connected in parallel or in series. When in parallel, full voltage is applied across each motor, causing it to run at base speed. When in series, the motor speeds are essentially one-half of base speed. Field-series resistance in shunt motors weakens the field, which causes the motors to run above the base speed. Speed range as high as 8:1 may be obtained in special motors. Armature-series resistance used with shunt or series motors produces motor speed below the base speed. In the series motor the field winding is also affected by the armature-series resistance, producing greater effect on the speed-torque characteristic than for the shunt motor where the field is constant. Speed control by this method is usually limited to approximately 50% of the base speed.

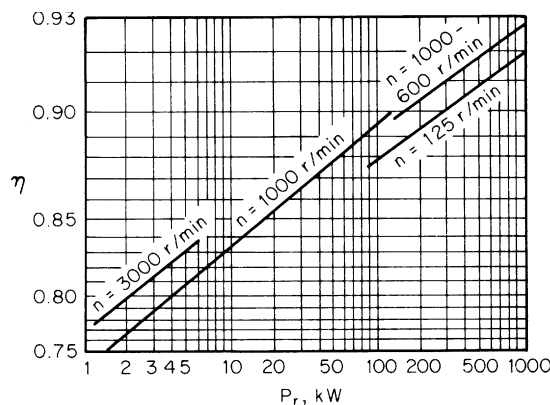


FIGURE 20-5 Typical efficiency curves of dc machines.

The above-speed control method results in power losses in the external resistors; solid-state dc motor control eliminates the power losses (see below).

Permanent-Magnet DC Motors. Permanent-magnet (PM) motors are available in fractional and low integral-horsepower sizes. They have several advantages over field-wound types. Excitation power supplies and associated wiring are not needed. Reliability is improved, since there are no exciting field coils to fail, and there is no likelihood of overspeed due to loss of field. Efficiency and cooling are improved by elimination of power loss in an exciting field. And the torque-versus-current characteristic is more nearly linear. Finally a PM motor may be used where a totally enclosed motor is required for a continuous-excitation duty cycle.

Temperature effects depend on the kind of magnet material used. Integral-horsepower motors with Alnico-type magnets are affected less by temperature than those with ceramic magnets because flux is constant. Ceramic magnets ordinarily used in fractional-horsepower motors have characteristics that vary about as much with temperature as do the shunt fields of excited machines.

Disadvantages are the absence of field control and special speed-torque characteristics. Overloads may cause partial demagnetization that changes motor speed and torque characteristics until magnetization is fully restored. Generally, an integral-horsepower PM motor is somewhat larger and more expensive than an equivalent shunt-wound motor, but total system cost may be less.

A PM motor is a compromise between compound-wound and series-wound motors. It has better starting torque, but approximately half the no-load speed of a series motor. In applications where compound motors are traditionally used, the PM motor could be considered where slightly higher efficiency and greater overload capacity are needed. In series-motor applications, cost consideration may influence the decision to switch. For example, in frame sizes under 5-in diameter the series motor is more economical. But in sizes larger than 5 in, the series motor costs more in high volumes. And the PM motor in these larger sizes challenges the series motor with its high torques and low no-load speed.

Brushless DC Motors. Brushless dc motors have a stationary armature and a rotating field structure, exactly opposite to how those elements are arranged in conventional dc motors. This construction speeds heat dissipation and reduces rotor inertia. Permanent magnets provide magnetic flux for the field. DC current to the armature is commutated with transistors rather than with the brushes and commutator bars of conventional dc motors.

Armatures of dc brushless motors typically contain 2 to 6 coils, whereas conventional dc motor armatures have from 10 to 50. Brushless motors have fewer coils because either two or four transistors are required to commutate each motor coil. This arrangement becomes increasingly costly and inefficient as the number of windings increases. A typical circuit of a brushless dc motor is shown in Fig. 20-6.

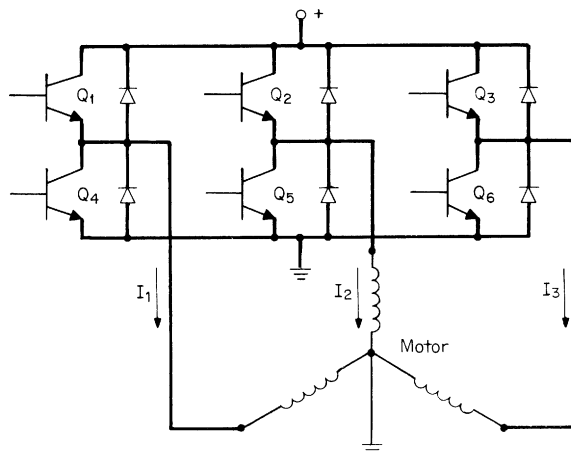


FIGURE 20-6 Typical circuit of a brushless dc motor.

The transistors controlling each winding of a dc brushless motor are turned on and off at specific rotor angles. The transistors provide current pulses to the armature windings that are similar to those provided by a commutator. The switching sequence is arranged to produce a rotating magnetic flux in the air gap that stays at a fixed angle to the flux produced by the permanent magnets on the rotor. Torque produced by a brushless dc motor is directly proportional to armature current.

DC Traction Motors. These are dc series motors typically rated 140 hp, 310 V, 2500 r/min. Four motors are used in each transit car, two on each axle. The power supply is 600 to 1000 V dc from the third rail, which is powered by 2500- to 5000-kW rectifier sets in rectifier substations located along the track. Starting and speed control are by either a cam controller or a chopper controller on board the transit car.

DC Servomotors. DC servomotors are high-performance motors normally used as prime movers in computers, numerically controlled machinery, or other applications where starts and stops must be made quickly and accurately. Servomotors have lightweight, low-inertia armatures that respond quickly to excitation-voltage changes. In addition, very low armature inductance in these motors results in a low electrical time constant (typically 0.05 to 1.5 ms) that further sharpens motor response to command signals. Servomotors include permanent-magnet, printed-circuit, and moving-coil (or shell) motors. The rotor of a shell motor consists of a cylindrical shell of copper or aluminum wire coils. The wire rotates in a magnetic field in the annular space between magnetic pole pieces and a stationary iron core. The field is provided by cast Alnico magnets whose magnetic axis is radial. The motor may have 2, 4, or 6 poles.

Each of these basic types has its own characteristics, such as inertia, physical shape, cost, shaft resonance, shaft configuration, speed, and weight. Although these motors have similar torque ratings, their physical and electrical constants vary considerably. The choice of a motor may be as simple as fitting one into the space available. However, this is generally not the case since most servosystems are very complex.

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20.3 SYNCHRONOUS MOTORS

Definition. A synchronous motor is a machine that transforms electric power into mechanical power. That average speed of normal operation is exactly proportional to the frequency of the system to which it is connected. Unless otherwise stated, it is generally understood that a synchronous motor has field poles excited with direct current.

Types. The synchronous motor is built with one set of ac polyphase distributed windings, designated the *armature*, which is usually on the stator and is committed to the ac supply system. The configuration of the opposite member, usually the rotor, determines the type of synchronous motor. Motors with dc excited field windings on salient-pole or round rotors, rated 200 to 100,000 hp and larger, are the dominant industrial type. In the brushless synchronous motor, the excitation (field current) is supplied through shaft-mounted rectifiers from an ac exciter. In the slip-ring

synchronous motor, the excitation is supplied from a shaft-mounted exciter or a separate dc power supply. Synchronous-induction motors rated below 5 hp, usually supplied from adjustable-speed drive inverters, are designed with a different reluctance across the air gap in the direct and quadrature axis to develop reluctance torque. The motors have no excitation source for synchronous operation. Synchronous motors below 1 hp usually employ a permanent-magnetic type of motor. These motors are usually driven by a transistor inverter from a dc source; they are termed *brushless dc motors*.

Standards. DC separately excited synchronous motors are covered by ANSI Standard C50.10-1965, Synchronous Machines, and C50.11-1965, Synchronous Motors. They are also covered by Part 21 of NEMA Standard MG-1 1972.

Theory of Operation. The operation of the dc separately excited synchronous motor can be explained in terms of the air-gap magnetic-field model, the circuit model, or the phasor diagram model of Fig. 20-7.

In the magnetic-field model of Fig. 20-7a, the stator windings are assumed to be connected to a polyphase source, so that the winding currents produce a rotating wave of current density J_a and radial armature reaction field B_a as explained below. The rotor carrying the main field poles is rotating in synchronism with these waves. The excited field poles produce a rotating wave of field B_d . The net magnetic field B_r is the spatial sum of B_a and B_d ; it induces an air-gap voltage V_{ag} in the stator windings, nearly equal to the source voltage V_r . The current-density distribution J_a is shown for the current I_a in phase with the voltage V_r , and $\text{pf} = 1$. The electromagnetic torque acting between the rotor and the stator is produced by the interaction of the main field B_d and the stator

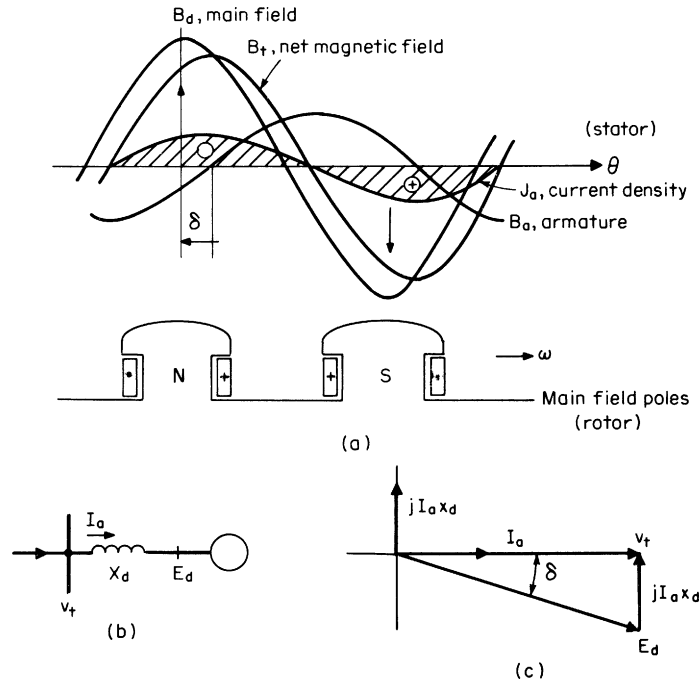


FIGURE 20-7 Operation of synchronous motor: (a) air-gap magnetic-field model; (b) circuit model; (c) phasor-diagram model.

current density J_a , as a $J \times B$ force on each unit volume of stator conductor. The force on the conductors is to the left ($-\phi$); the reaction force on the rotor is to the right ($+\phi$), and in the direction of rotation.

The operation of the synchronous motor can be represented by the circuit model of Fig. 20-7b. The motor is characterized by its synchronous reactance x_d and the excitation voltage E_d behind x_d . The model neglects saliency (poles), saturation, and armature resistance, and is suitable for first-order analysis, but not for calculation of specific operating points, losses, field current, and starting.

The phasor diagram of Fig. 20-7c is drawn for the field model and circuit model previously described. The phasor diagram neglects saliency and armature resistance. The phasors correspond to the waves in the field model. The terminal voltage V_t is generated by the field B_f ; the excitation voltage E_d is generated by the main field B_d ; the voltage drop $jI_a x_d$ is generated by the armature reaction field B_a ; and the current I_a is the aggregate of the current-density wave J_a . The power angle δ is that between V_t and E_d , or between B_f and B_d . The excitation voltage E_d , in per-unit (pu),* is equal to the field current I_{fd} , in pu, on the air-gap line of the no-load (open-circuit) saturation curve of the machine.

Power-Factor Correction. Synchronous motors were first used because they were capable of raising the power factor of systems having large induction-motor loads. Now they are also used because they can maintain the terminal voltage on a weak system (high source impedance), they have lower cost, and they are more efficient than corresponding induction motors, particularly the low-speed motors. Synchronous motors are built for operation at pf = 1.0, or pf = 0.8 lead, the latter being higher in cost and slightly less efficient at full load.

The selection of a synchronous motor to correct an existing factor is merely a matter of bookkeeping of active and reactive power. The synchronous motor can be selected to correct the overall power factor to a given value, in which case it must also be large enough to accomplish its motoring functions; or it can be selected for its motoring function and required to provide the maximum correction that it can when operating at pf = 0.8 lead. In Fig. 20-8, a power diagram shows how the active and reactive power components P_s and Q_s of the synchronous motor are added to the components P_i and Q_i of an induction motor to obtain the total P_t and Q_t components, the kVA_t, and the power factor. The Q_s of the synchronous motor is based on the rated kVA and pf = 0.8 lead, rather than the actual operating kVA.

The synchronous motor can support the voltage of a weak system, so that a larger-rated synchronous motor can be installed than an induction motor for the same source impedance. With an induction motor, both the P and Q components produce voltage drops in the source impedance. With a synchronous motor operating at leading power factor, the P component produces a voltage drop in the source resistance, but the Q component produces a voltage rise in the source reactance that can offset the drop and allow the terminal voltage to be normal. If necessary, the field current of the synchronous motor can be controlled by a voltage regulator connected to the motor bus. The leading current of a synchronous motor is able

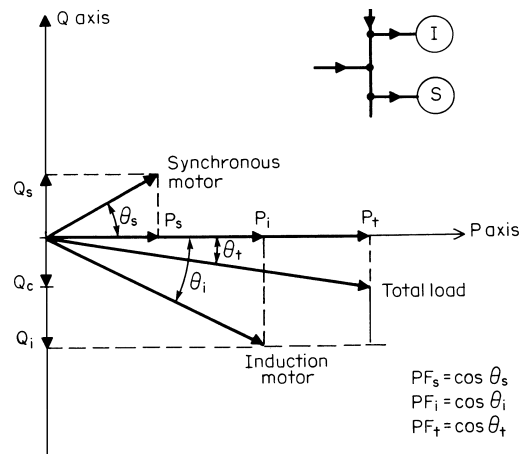


FIGURE 20-8 Power diagram of induction motor and synchronous motor operating in parallel, showing component and net values of P and Q .

* A reference unit for expressing all parameters on a common reference base. One pu is 100% of the chosen base.

to develop a sufficient voltage rise through the source reactance to overcome the voltage drop and maintain the motor voltage equal to the source voltage.

Starting. The interaction of the main field produced by the rotor and the armature current of the stator will produce a net average torque to drive the synchronous motor only when the rotor is revolving at speed n in synchronism with the line frequency f ; $n = 120 f/p$, p = poles. The motor must be started by developing other than synchronous torques. Practically, the motor is equipped with an induction-motor-type squirrel-cage winding on the rotor, in the form of a damper winding, in order to start the motor.

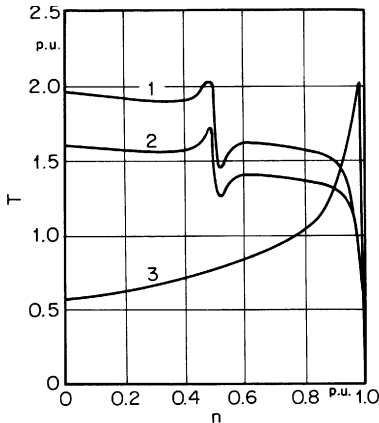


FIGURE 20-9 Characteristic torque curves for 5000-hp synchronous induction motor during runup at full voltage: (1) synchronous motor for $pf = 1$; (2) synchronous motor for $pf = 0.8$; (3) squirrel-cage induction motor.

The motor is started on the damper windings with the field winding short-circuited, or terminated in a resistor, to attenuate the high “transformer”-induced voltages. When the motor reaches the lowest slip speed, practically synchronous speed, the field current is applied to the field winding, and the rotor poles accelerate and pull into step with the synchronously rotating air-gap magnetic field. The damper windings see zero slip and carry no further current, unless the rotor oscillates with respect to the synchronous speed.

Starting curves for a synchronous motor are shown in Fig. 20-9. The damper winding is designed for high starting torque, as compared to an induction motor of the same rating. The closed field winding contributes to the starting torque in the manner of a 3-phase induction motor with a 1-phase rotor. The field winding produces positive torque to half speed, then negative torque to full speed, accounting for the anomaly at half speed. The maximum and minimum torque excursion at the anomaly is reduced by the resistance in the closed field winding circuit during starting. The effect is increased by the design of the damper winding.

The velocity of the rotor during the synchronizing phase, after field current is applied, is shown in Fig. 20-10. The rotor is assumed running at 0.05 pu slip on the damper winding. The undulation in speed, curve 1, is the effect of the poles attempting to synchronize the rotor just by reluctance torque. The added effect of the field current is shown by curve 2, and the resultant by curve 3. The effect of the reluctance torque of curve 1 is not dependent on pole polarity. The synchronizing torque of curve 2, with the field current applied, is pole polarity dependent; the poles want to match the air-gap

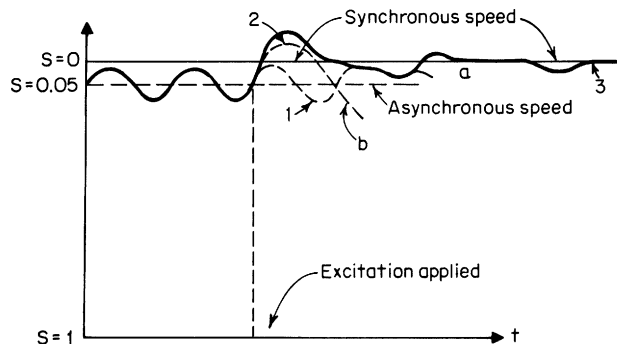


FIGURE 20-10 Relationship between slip and time for a synchronous motor pulling into synchronism: (a) successful; (b) unsuccessful.

TABLE 20-1 Locked-Rotor, Pull-In, and Pull-Out Torques for Synchronous Motors

r/min	hp	Percent of rated full-load torque*			
		Locked rotor	Pull-in (based on normal Wk^2 of load) [†]	Pull-out [‡]	
				1.0 pf	0.8 pf
514 to 1800	200 and below; 1.0 pf }	100	100	150	175
	150 and below; 0.8 pf }				
	250 to 1000; 1.0 pf }	60	60	150	175
	200 to 1000; 0.8 pf }				
450 and below	1250 and larger	40	60	150	175
	All ratings	40	30	150	200

*The torque values with other than rated voltage applied are approximately equal to the rated voltage values multiplied by the ratio of the actual voltage to rated voltage in the case of the pull-out torque, and multiplied by the square of this ratio in the case of the locked-rotor and pull-in torque.

[†]With rated excitation current applied.

field in the forward torque direction. Curve *a* shows a successful synchronization. Curve *b* shows the condition of too much load or inertia to synchronize.

Torque Definitions. The torques described in the following paragraphs are listed in the Standards. The minimum values are given in Table 20-1.

Locked-rotor torque is the minimum torque, which the synchronous motor will develop at rest for all angular positions of the rotor, with rated voltage at rated frequency applied.

Pull-in torque is the maximum constant-load torque under which the motor will pull into synchronism, at rated voltage and frequency, when its rated field current is applied. Whether the motor can pull the load into step from the slip running on the damper windings depends on the speed-torque character of the load and the total inertia of the revolving parts. A typical relationship between maximum slip and percent of normal Wk^2 for pulling into step is shown in Fig. 20-11. Table 20-1 specifies minimum values of pull-in torque with the motor loaded with normal Wk^2 ; these values are given below. (See also Table 20-1.) *Nominal pull-in torque* is the value at 95% of synchronous speed, with rated voltage at rated frequency applied, when the motor is running on the damper windings.

Pull-out torque is the maximum sustained torque which the motor will develop at synchronous speed for 1 min, with rated voltage at rated frequency applied, and with rated field current.

In addition, the *pull-up torque* is defined as the minimum torque developed between standstill and the pull-in point. This torque must exceed the load torque by a sufficient margin to assure satisfactory acceleration of the load during starting.

The *reluctance torque* is a component of the total torque when the motor is operating synchronously. It results from the saliency of the poles and is a manifestation of the poles attempting to align themselves with the air-gap magnetic field. It can account for up to 30% of the pull-out torque.

The *synchronous torque* is the total steady-state torque available, with field excitation applied, to drive the motor and the load at synchronous speed. The maximum value as the motor is loaded is the pull-out torque, developed as a power angle $\delta = 90^\circ$.

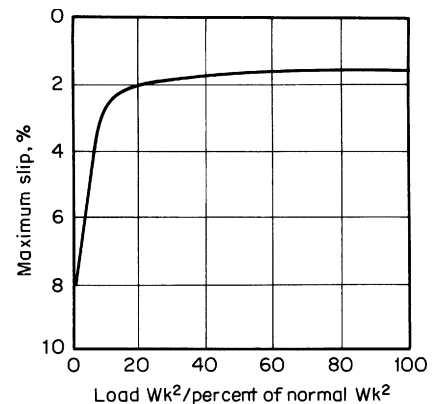


FIGURE 20-11 Typical relationship between load inertia and maximum slip for pulling synchronous motors into step.

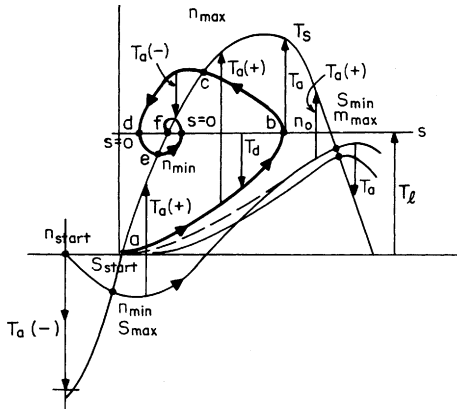


FIGURE 20-12 Locus of torque and speed versus power angle δ for a synchronous motor during a successful attempt and an unsuccessful attempt to synchronize.

$T_d - T_l$. In the figure, the closing angle is assumed zero at point a . Furthermore, $T_d = T_l$, so that the residual torque T_a is zero. The rotor has a finite slip, so that the power angle δ increases. As it does, the synchronous torque T_s increases, T_d increases and the rotor accelerates to point b , where $n = n_0$, $T_d = 0$. The slip goes negative, reverses the direction of the damper torque, but the rotor continues to accelerate to point c , where the speed is maximum and the accelerating torque is zero. The rotor falls back to points d and e at minimum speed, accelerates again, and finally synchronizes at point f .

If the initial slip is excessive, or if the inertia and/or load too great, the locus in Fig. 20-12 could follow the path ab' . The condition of $T_a = 0$ is reached below synchronous speed; the rotor never pulls into step, but oscillates around the initial slip velocity until the machine is tripped off.

Damper Windings. Damper windings are placed on the rotors of synchronous motors for two purposes: for starting and for reducing the amplitude of power-angle oscillation. The damper windings consist of copper or brass bars inserted through holes in the pole shoes and connected at the ends to rings to form the equivalent of a squirrel cage. The rings can extend between the poles to form a complete damper. Synchronous motors with solid pole shoes, or solid rotors, perform like motors with damper windings.

The design of the damper winding requires the selection of the bar and ring material to meet the

torque and damping requirements. Figure 20-13 shows the effect on the starting curves for the damper winding of varying the material from a low-resistance copper in curve 1, to a higher-resistance brass or aluminum-bronze alloy in curve 2. Curve 1 gives a starting torque of about 0.25 pu, and a pull-in torque of 1.0 pu, of the nominal synchronous torque. Curve 2 gives a higher starting torque of about 0.5 to 1.0 pu, but a pull-in torque of about 0.4 pu of the nominal value. The additional starting torque of the field winding is superimposed on the torque of the damper alone. The damper winding must be designed to meet the characteristics of the load.

To design the damper winding so that the amplitude of the natural-frequency oscillation is reduced, the bar currents during the low-frequency

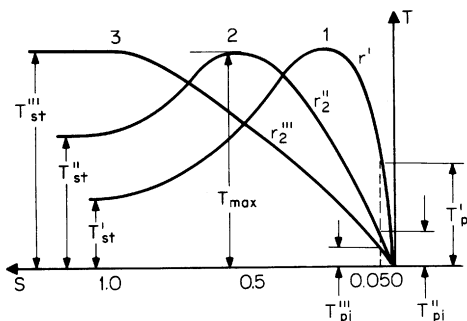


FIGURE 20-13 Effect of resistivity of damper material on the starting and pull-in torque of the synchronous motor. Damper winding 1, least resistance; damper winding 3, maximum resistance.

sweeping of the air-gap flux across the pole faces must be maximized. Since the slip frequency is low, the currents and damper effectiveness are maximized by making the dampers low resistance, corresponding to curve 1 in Fig. 20-13. This design coincides with the requirement for low starting torque and high pull-in torque. In special cases, the equivalent of a deep-bar or double-bar damper can be used, if there is adequate space on the pole shoe.

Methods of Starting. The method used to start a synchronous motor depends on two factors: the required torque to start the load and the maximum starting current permitted from the line. Basically, the motor is started by using the damper windings to develop asynchronous torque or by using an auxiliary motor to bring the unloaded motor up to synchronous speed. Solid-state converters have also been used to bring up to speed large several-hundred-MVA synchronous motor/generators for pumped storage plants.

Techniques for asynchronous starting on the damper windings are the same as for squirrel-cage induction motors of equivalent rating. Across-the-line starting provides the maximum starting torque, but requires the maximum line current. The blocked-rotor kVA of synchronous motors as a function of pole number is shown in Fig. 20-14. If the ac line to the motor supplies other loads, the short-circuit kVA of the line must be at least 6 to 10 times the blocked rotor kVA of the motor to limit the line-voltage dip on starting. The starting and pull-in torques for three general classes of synchronous motors are shown in Fig. 20-15. The torques are shown for rated voltage; for across-the-line starting, the values will be reduced to V_t^2 (pu).

Reduced-voltage starting is used where the full starting torque of the motor is not required and/or the ac line cannot tolerate the full starting current. The starter includes a 3-phase open-delta or 3-winding autotransformer, which can be set to apply 50%, 65%, or 80% of line voltage to the motor on the first step. The corresponding torque is reduced to 25%, 42%, or 64%. The starter switches the motor to full voltage when it has reached nearly synchronous speed, and then applies the field excitation to synchronize the motor.

ANSI C50.11-1965 limits the number of starts for a synchronous motor, under its design conditions of Wk^2 , load torque, nominal voltage, and starting method, to the following:

1. Two starts in succession, coasting to rest between starts, with the motor initially at ambient temperature, or
2. One start with the motor initially at a temperature not exceeding its rated load operating temperature.

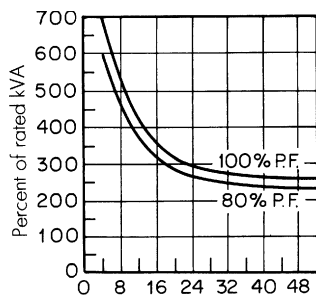


FIGURE 20-14 Approximate blocked-rotor kVA of synchronous motors.

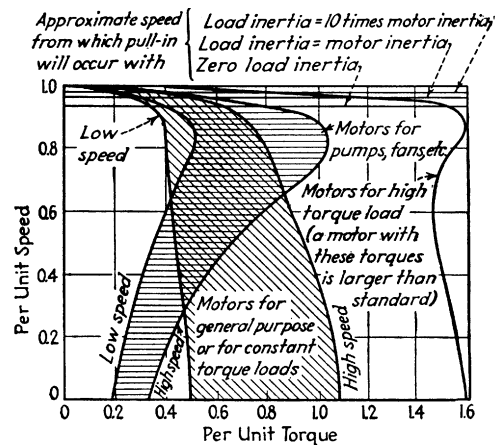


FIGURE 20-15 Approximate starting performance of synchronous motors.

If additional starts are required, it is recommended that none be made until all conditions affecting operation have been thoroughly investigated and the apparatus examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum since the life of the motor is affected by the number of starts.

Exciters. DC separately excited synchronous motors are provided with a shaft-driven exciter to supply the field power. Exciters are classified into slip-ring types and brushless types. The slip-ring type consists of a dc generator, whose output is fed into the motor field winding through slip rings and stationary brushes. The brushless type consists of an ac generator, with rotating armature and stationary field; the output is rectified by solid-state rectifier elements mounted on the rotating structure and fed directly to the motor field winding. In each type, the motor field current is controlled by the exciter field current. Typical kilowatt ratings for exciters for 60-Hz synchronous motors are given in MG1-21.16 as a function of hp rating, speed, and power factor. For a given hp rating, the excitor kW increases as the speed is reduced, and as the power factor is shifted from $\text{pf} = 1.0$ to $\text{pf} = 0.8$ lead.

During starting, the motor field winding must be disconnected from the exciter and loaded with a resistor, to limit the high induced voltage, to prevent damage to the rectifier elements of the brushless type, and to prevent the circulation of ac current through a slip-ring-type dc exciter. The switching is done with a contactor for the slip-ring type, and with thyristors on the rotating rectifier assembly for the brushless type. Except for the disconnection for starting, the synchronous-motor excitation system is practically the same as for an ac generator of the same rating.

Brushless-type exciters are now used on all new high-speed synchronous motors (2 to 8 poles) that formerly were built with direct-drive dc exciters and slip rings. The brushless-type exciters require minimum maintenance and can be used in explosive-atmospheres. The circuit of a typical brushless-type excitation system is shown in Fig. 20-16. The semicontrolled bridge with three diodes and three thyristors rectifies the output of the ac exciter generator and supplies the motor field winding. The thyristors act as a switch to open the rectifier during starting and to close it during running, whereas the ac exciter generator is excited with its own field current. The resistor is permanently connected across the motor field winding during starting and running. It improves the torque characteristics during

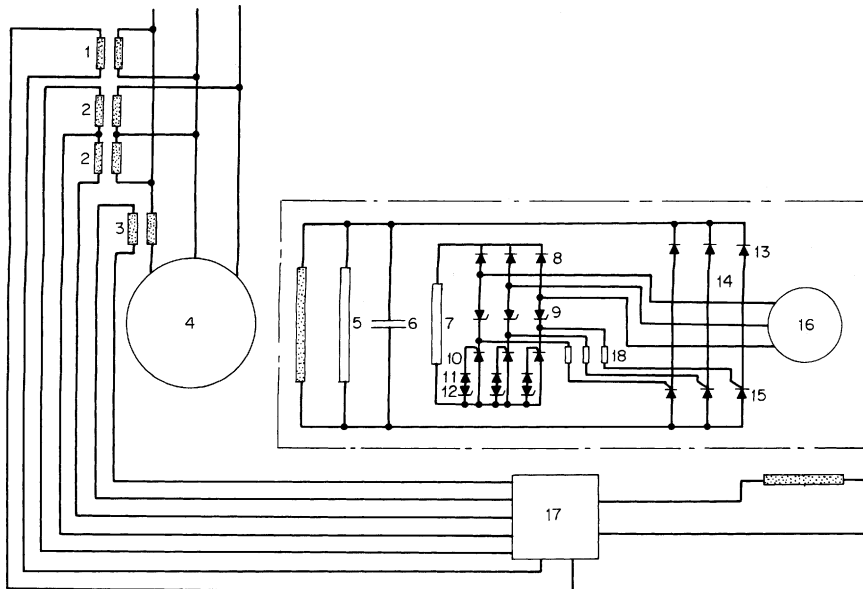


FIGURE 20-16 Brushless-type excitation system for a synchronous motor.

starting, and protects the bridge elements against transient overvoltages during running. The capacitor protects the diodes and thyristors against commutation overvoltages caused by hole-storage phenomena in conjunction with the inductances of the armature windings of the ac exciter generator.

The control system (Fig. 20-16) comprises a simple auxiliary rectifier arrangement connected in parallel with the main rectifier bridge and loaded with an auxiliary resistor 7. Each main thyristor has an auxiliary thyristor that provides the gate current and operates on the same phase of the ac exciter voltage. Consequently the trigger signal always occurs at the correct instant, that is, when the thyristors have a forward loading. No trigger signal is given during the blocking period. There is no excitation at the exciter during run-up, and therefore no trigger signal is applied to the gates of the thyristors and they remain blocking. The alternating current induced in the field winding flows in both directions through the protection resistor 5. When the machine has been run up to normal speed, the field voltage is applied to the ac exciter. It then supplies the control current and the thyristors are fired. Control losses are only 0.1% to 0.2% of the exciter power and are therefore negligible. The auxiliary thyristor 10 together with the diode 11 and Zener diode 12 prevents preignition of the thyristors during run-up due to high residual voltage in the ac exciter. On the other hand, the gates of the other thyristors are protected against overload by Zener diode 9 and resistor 18. If the voltage exceeds the Zener voltage, the Zener diode conducts the excess current.

Standard Ratings. Standard ratings for dc separately excited synchronous motors are given in NEMA MG1-1978, Part 21. Standard horsepower ratings range from 20 to 100,000 hp. Speed ratings extend from 3600 r/min (2-pole) to 80 r/min (90-pole) for 60-Hz machines, and five-sixths of the values for 50-Hz machines. The power factor shall be unity or 0.8 leading. The voltage ratings for 60-Hz motors are 200, 230, 460, 575, 2300, 4000, 4600, 6600, and 13,200 V. It is not practical to build motors of all horsepower ratings at these speeds and voltages.

Efficiency. Efficiency and losses shall be determined in accordance with IEEE test procedures for synchronous machines, Publication 115. The efficiency shall be determined at rated output, voltage, frequency, and power factor. The following losses shall be included in determining the efficiency: (1) I^2R loss of armature and field; (2) core loss; (3) stray-load loss; (4) friction and windage loss; and (5) exciter loss for shaft-driven exciter. The resistances should be corrected for temperature.

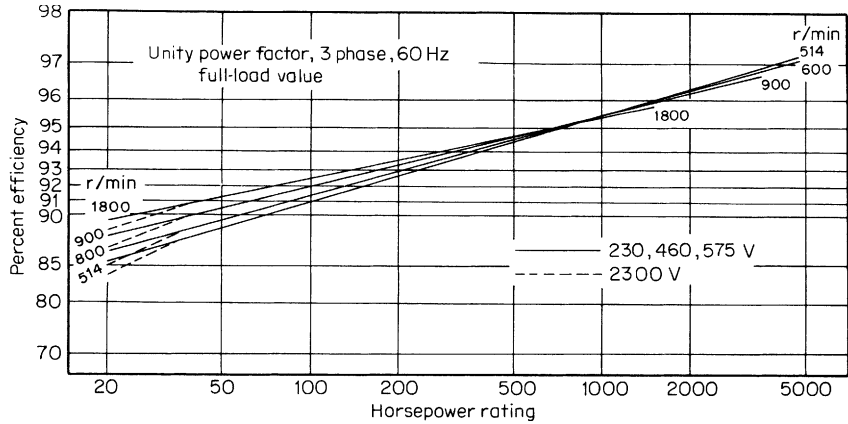
Typical synchronous motor efficiencies are shown in Fig. 20-17. The unity-power-factor synchronous motor—historically up to 3% more efficient than the NEMA design B induction motor, is now only 1% to 2% more efficient because of improvements in NEMA B designs and manufacturing techniques.

The 0.8 pf synchronous motor, because of the increased copper loss, is lower in efficiency; its efficiency is closer to that of the induction motor at high speed, but better at low speed.

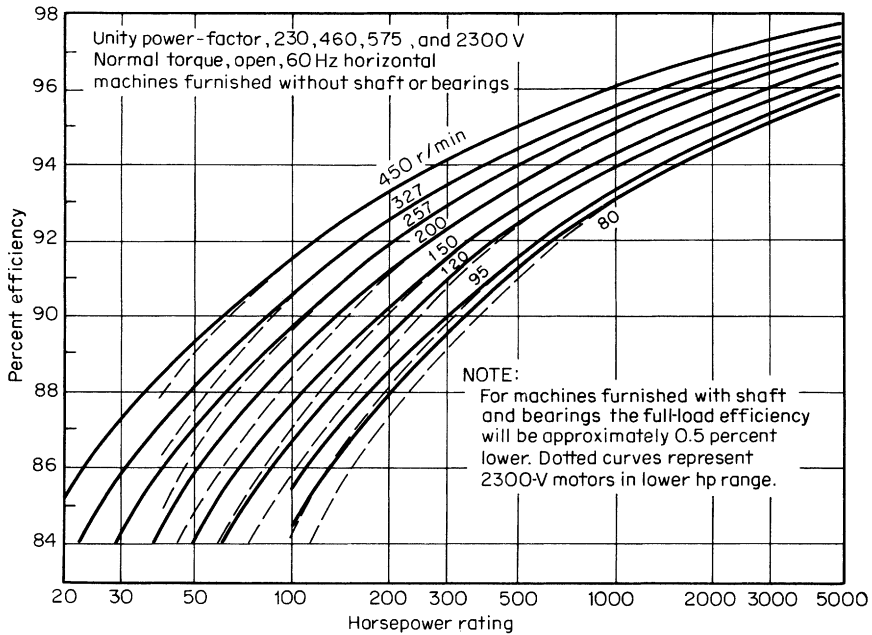
Standard Tests. Tests on synchronous motors shall be made in accordance with *IEEE Test Procedure for Synchronous Machines*, Publ. No. 115, and ANSI C50.10-1965. The following tests shall be made on motors completely assembled in the factory and furnished with shaft and complete set of bearings: resistance test of armature and field windings; dielectric test of armature and field windings; mechanical balance; current balance at no load; and direction of rotation. The following tests may be specified on the same or duplicate motors: locked-rotor current; temperature rise; locked-rotor torque; overspeed; harmonic analysis and TIF; segregated losses; short-circuit tests at reduced voltage to determine reactances and time constants; field-winding impedance; and speed-torque curve.

The following tests shall be made on all motors not completely assembled in the factory: resistance and dielectric tests of armature and field windings. The following field tests are recommended after installation: resistance and dielectric tests of armature and field windings not completely assembled in the factory; mechanical balance; bearing insulation; current balance at no load; direction of rotation. The following field tests may be specified on the same or duplicate motors: temperature rise; short-circuit tests at reduced voltage to determine reactances and time constants; field-winding impedance.

The dielectric test for the armature winding shall be conducted for 1 min, with an ac rms voltage of 1000 V plus twice the rated voltage. For machines rated 6 kV and above, the test may be conducted with a dc voltage of 1.7 times the ac rms test value. The dielectric test for the field winding depends upon the connection for starting. For a short-circuited field winding, the ac rms test voltage is 10 times



(a)



(b)

FIGURE 20-17 Full-load efficiencies of (a) high-speed general-purpose synchronous motors and (b) low-speed synchronous motors.

the rated excitation voltage, but no less than 2500 V, nor more than 5000 V. For a field winding closed through a resistor, the ac rms test voltage is twice the rms value of the IR drop, but not less than 2500 V, where the current is the value that would circulate with a short-circuited winding. When a test is made on an assembled group of several pieces of new apparatus, each of which has passed a high-potential test, the test voltage shall not exceed 85% of the lowest test voltage for any part of the group. When a test is made after installation of a new machine, which has passed its high-potential test at the factory and whose windings have not since been disturbed, the test voltages should be 75% of the original values.

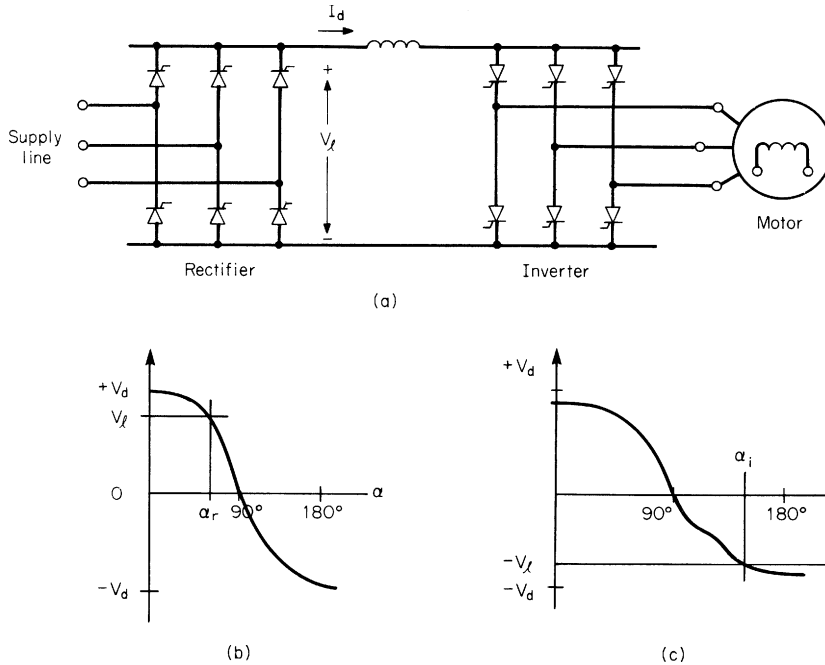


FIGURE 20-19 Diagram of (a) machine-commutated synchronous motor drive; (b) dc voltage vs. firing angle α_r , characteristic of rectifier; (c) dc voltage versus firing angle α_i , characteristic of inverter.

dc voltage V_f for the link. The firing angle of the inverter is set at α_i in the inverting quadrant of the converter so that the link voltage V_f matches the internal ac voltage generated by the motor at the given speed. Power flows from the rectifier at $V_f I_d$ into the inverter and the motor. The inverter firing signals are synchronized to the motor voltage. For decelerating the motor, the rectifier and inverter functions are reversed by shifting the firing angles. Power flows from the motor into the dc link and to the supply line.

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20.4 INDUCTION MACHINES

20.4.1 Theory of the Polyphase Induction Motor

Principle of Operation. An induction motor is simply an electric transformer whose magnetic circuit is separated by an air gap into two relatively movable portions, one carrying the primary and the other the secondary winding. Alternating current supplied to the primary winding from an electric

power system induces an opposing current in the secondary winding, when the latter is short-circuited or closed through an external impedance. Relative motion between the primary and secondary structures is produced by the electromagnetic forces corresponding to the power thus transferred across the air gap by induction. The essential feature that distinguishes the induction machine from other types of electric motors is that the secondary currents are created solely by induction, as in a transformer, instead of being supplied by a dc exciter or other external power source, as in synchronous and dc machines.

Induction motors are classified as squirrel-cage motors and wound-rotor motors. The secondary windings on the rotors of squirrel-cage motors are assembled from conductor bars short-circuited by end rings or are cast in place from a conductive alloy. The secondary windings of wound-rotor motors are wound with discrete conductors with the same number of poles as the primary winding on the stator. The rotor windings are terminated on slip rings on the motor shaft. The windings can be short-circuited by brushes bearing on the slip rings, or they can be connected to resistors or solid-state converters for starting and speed control.

Construction Features. The normal structure of an induction motor consists of a cylindrical rotor carrying the secondary winding in slots on its outer periphery and an encircling annular core of laminated steel carrying the primary winding in slots on its inner periphery. The primary winding is commonly arranged for 3-phase power supply, with three sets of exactly similar multipolar coil groups spaced one-third of a pole pitch apart. The superposition of the three stationary, but alternating, magnetic fields produced by the 3-phase windings produces a sinusoidally distributed magnetic field revolving in synchronism with the power-supply frequency, the time of travel of the field crest from 1-phase winding to the next being fixed by the time interval between the reaching of their crest values by the corresponding phase currents. The direction of rotation is fixed by the time sequence of the currents in successive phase belts and so may be reversed by reversing the connections of one phase of a 2- or 3-phase motor.

Figure 20-20 shows the cross section of a typical polyphase induction motor, having in this case a 3-phase 4-pole primary winding with 36 stator and 28 rotor slots. The primary winding is composed

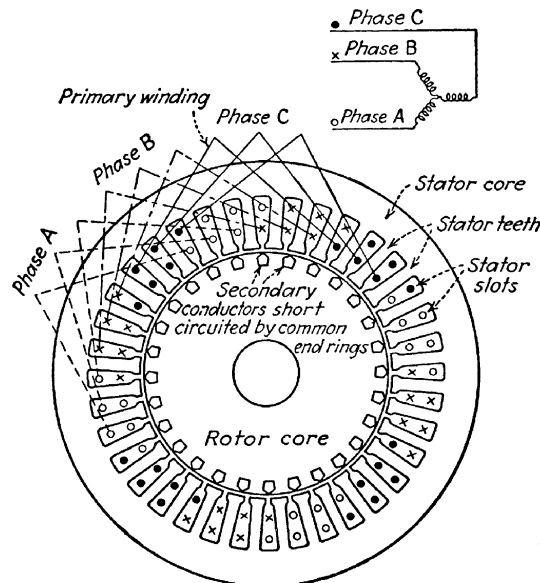


FIGURE 20-20 Section of squirrel-cage induction motor, 3-phase, 4-pole, $\frac{5}{6}$ -pitch stator winding.

of 36 identical coils, each spanning 8 teeth, one less than the 9 teeth in one pole pitch. The winding is therefore said to have $\frac{8}{9}$ pitch. As there are three primary slots per pole per phase, phase A comprises four equally spaced "phase belts," each consisting of three consecutive coils connected in series. Owing to the short pitch, the top and bottom coil sides of each phase overlap the next phase on either side. The rotor, or secondary, winding consists merely of 28 identical copper or cast-aluminum bars solidly connected to conducting end rings on each end, thus forming a "squirrel-cage" structure.

Both rotor and stator cores are usually built on silicon-steel laminations, with partly closed slots, to obtain the greatest possible peripheral area for carrying magnetic flux across the air gap.

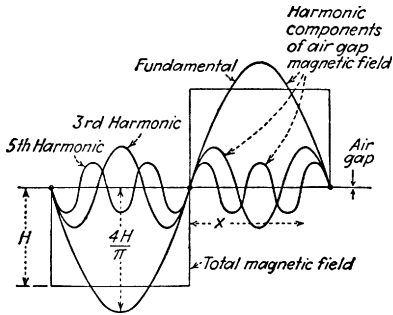


FIGURE 20-21 Magnetic field produced by a single coil.

The Revolving Field. The key to understanding the induction motor is a thorough comprehension of the revolving magnetic field.

The rectangular wave in Fig. 20-21 represents the mmf, or field distribution, produced by a single full-pitch coil, carrying H At. The air gap between stator and rotor is assumed to be uniform, and the effects of slot openings are neglected. To calculate the resultant field produced by the entire winding, it is most convenient to analyze the field of each single coil into its space-harmonic components, as indicated in Fig. 20-21 or expressed by the following equation:

$$H(x) = \frac{4H}{\pi} \left(\sin x + \frac{1}{3} \sin 3x + \frac{1}{5} \sin 5x + \frac{1}{7} \sin 7x + \dots \right) \quad (20-8)$$

When two such fields produced by coils in adjacent slots are superposed, the two fundamental sine-wave components will be displaced by the slot angle θ , the third-harmonic components by the angle 3θ , the fifth harmonics by the angle 5θ , etc. Thus, the higher space-harmonic components in the resultant field are relatively much reduced as compared with the fundamental. By this effect of distributing the winding in several slots for each phase belt, and because of the further reductions due to fractional pitch and to phase connections, the space-harmonic fields in a normal motor are reduced to negligible values, leaving only the fundamental sine wave components to be considered in determining the operating characteristics.

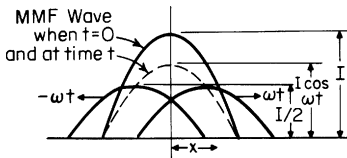


FIGURE 20-22 Resolution of alternating wave into two constant-magnitude waves revolving in opposite directions.

The alternating current flowing in the winding of each phase therefore produces a sine-wave distribution of magnetic flux around the periphery, stationary in space but varying sinusoidally in time in synchronism with the supply frequencies. Referring to Fig. 20-22, the field of phase A at an angular distance x from the phase axis may be represented as an alternating phasor $I \cos x \cos \omega t$ but may equally well be considered as the resultant of two phasors constant in magnitude but revolving in opposite directions at synchronous speed:

$$I \cos x \cos \omega t = \frac{I}{2} [\cos (x - \omega t) + \cos (x + \omega t)] \quad (20-9)$$

Each of the right-hand terms in this equation represents a sine-wave field revolving at the uniform rate of one pole pitch, or 180 elec deg, in the time of each half cycle of the supply frequency. The synchronous speed N_s of a motor is therefore given by

$$N_s = \frac{120f}{P} \quad \text{r/min} \quad (20-10)$$

where f = line frequency in hertz and P = number of poles of the winding.

Considering phase A alone (Fig. 20-23), two revolving fields will coincide along the phase center line at the instant its current is a maximum. One-third of a cycle later, each will have traveled 120 elec deg, one forward and the other backward, the former lining up with the axis of phase B and the latter with the axis of phase C. But at this moment, the current in phase B is a maximum, so that the forward-revolving B field coincides with the forward A field, and these two continue to revolve together. The backward B field is 240° behind the backward A field, and these two remain at this angle, as they continue to revolve. After another third of a cycle, the forward A and B fields will reach the phase C axis, at the same moment that phase C current becomes a maximum. Hence, the forward fields of all three phases are directly additive, and together they create a constant-magnitude sine-wave-shaped synchronously revolving field with a crest value two-thirds the maximum instantaneous value of the alternating field due to one phase alone. The backward-revolving fields of the three phases are separated by 120°, and their resultant is therefore zero so long as the 3-phase currents are balanced in both magnitude and phase.

If a 2-phase motor is considered, it will have two 90° phase belts per pole instead of three 60° phase belts, and a similar analysis shows that it will have a forward-revolving constant-magnitude field with a crest value equal to the peak value of one phase alone and will have zero backward-revolving fundamental field. A single-phase motor will have equal forward and backward fields and so will have no tendency to start unless one of the fields is suppressed or modified in some way.

While the space-harmonic-field components are usually negligible in standard motors, it is important to the designer to recognize that there will always be residual harmonic-field values which may cause torque irregularities and extra losses if they are not minimized by an adequate number of slots and correct winding distribution. An analysis similar to that given for the fundamental field shows that in all cases the harmonic fields corresponding to the number of primary slots (seventh and nineteenth in a nine-slot-per-pole motor) are important and that the fifth and seventh harmonics on 3-phase, or third and fifth on 2-phase, may also be important.

The third-harmonic fields and all multiples of the third are zero in a 3-phase motor, since the mmf's of the three phases are 120° apart for both backward and forward components of all of them. Finally, therefore, a 3-phase motor has the following distinct fields:

1. The fundamental field with P poles revolving forward at speed N_s .
2. A fifth-harmonic field with $5P$ poles revolving backward at speed $N_s/5$.
3. A seventh-harmonic field with $7P$ poles revolving forward at speed $N_s/7$.
4. Similar thirteenth, nineteenth, twenty-fifth, etc., forward-revolving and eleventh, seventeenth, twenty-third, etc., backward-revolving harmonic fields.

Figure 20-24 shows a test speed-torque curve obtained on a 2-phase squirrel-cage induction motor with straight (unspiraled) slots. The torque dips due to three of the forward-revolving fields are clearly indicated.

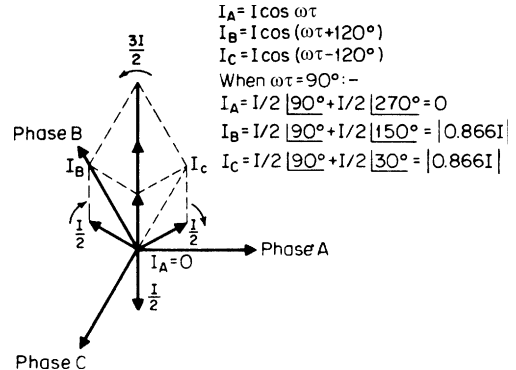


FIGURE 20-23 Resolution of alternating emf of each phase into oppositely revolving constant-magnitude components shown at instant when phase A current is zero ($\omega\tau = 90^\circ$).

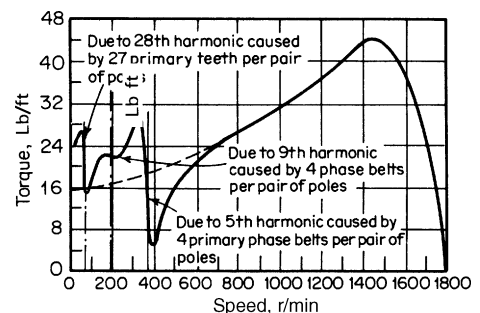


FIGURE 20-24 Speed-torque curve of 2-phase motor showing harmonic torque.

Torque, Slip, and Rotor Impedance. When the rotor is stationary, the revolving magnetic field cuts the short-circuited secondary conductors at synchronous speed and induces in them line-frequency currents. To supply the secondary IR voltage drop, there must be a component of voltage in time phase with the secondary current, and the secondary current, therefore, must lag in space position behind the revolving air-gap field. A torque is then produced corresponding to the product of the air-gap field by the secondary current times the sine of the angle of their space-phase displacement.

At standstill, the secondary current is equal to the air-gap voltage divided by the secondary impedance at line frequency, or

$$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{R_2 + jX_2} \quad (20-11)$$

where R_2 = effective secondary resistance and X_2 = secondary leakage reactance at primary frequency.

The speed at which the magnetic field cuts the secondary conductors is equal to the difference between the synchronous speed and the actual rotor speed. The ratio of the speed of the field relative to the rotor to synchronous speed is called the slip s

$$s = \frac{N_s - N}{N_s} \quad (20-12)$$

or

$$N = (1 - s)N_s$$

where N = actual and N_s = synchronous rotor speed.

As the rotor speeds up, with a given air-gap field, the secondary induced voltage and frequency both decrease in proportion to s . Thus, the secondary voltage becomes sE_2 , and the secondary impedance $R_2 + jsX_2$, or

$$I_2 = \frac{sE_2}{R_2 + jsX_2} = \frac{E_2}{(R_2/s) + jX_2} \quad (20-13)$$

The only way that the primary is affected by a change in the rotor speed, therefore, is that the secondary resistance as viewed from the primary varies inversely with the slip.

In practice, the effective secondary resistance and reactance, or R_2 and X_2 , change with the secondary frequency, owing to the varying "skin effect," or current shifting into the outer portion of the conductors, when the frequency is high. This effect is employed to make the resistance, and therefore the torque, higher at starting and low motor speeds, by providing a double cage, or deep-bar construction, as shown in Fig. 20-25. The leakage flux between the outer and inner bars makes the inner-bar reactance high, so that most of the current must flow in the outer bars or at the top of a deep bar at standstill, when frequency is high. At full speed, the secondary frequency is very low, and most of the current flows in the inner bars, or all over the cross section of a deep bar, owing to their lower resistance.

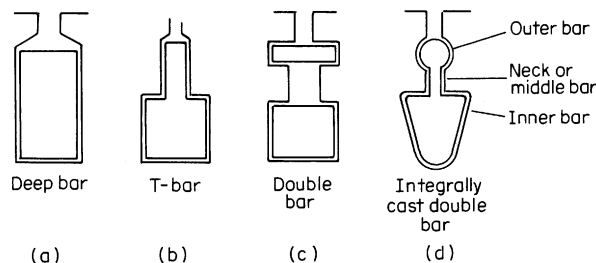


FIGURE 20-25 Alternative forms of squirrel cage rotor bars.

Analysis of Induction Motors. Induction motors are analyzed by two methods: (1) circle diagram and (2) equivalent circuit. The two methods are used for steady-state conditions. The circle diagram is convenient for visualizing overall performance but is too inaccurate for detailed calculations and design. The magnetizing current is not constant, but decreases with load because of the primary impedance drop. All of the circuit constants vary over the operating range due to magnetic saturation and skin effect. The equivalent circuit method predominates for analysis and design under steady-state conditions. The impedances can be adjusted to fit the conditions at each calculation point.

Circle Diagram. The voltage-current relations of the polyphase induction machine are roughly indicated by the circuit of Fig. 20-26. The magnetizing current I_M proportional to the voltage and lagging 90° in phase is nearly constant over the operating range, while the load current varies inversely with the sum of primary and secondary impedances. As the slip s increases, the load current and its angle of lag behind the voltage both increase, following a nearly circular locus. Thus, the circle diagram (Fig. 20-27) provides a picture of the motor behavior.

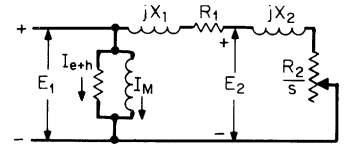


FIGURE 20-26 Equivalent circuit for circle diagram.

The data needed to construct the diagram are the magnitude of the no-load current ON and of the blocked-rotor current OS and their phase angles with reference to the line voltage OE . A circle with its center on the line NU at right angles to OE is drawn to pass through N and S . Each line on the diagram can be measured directly in amperes, but it also represents voltamperes or power, when multiplied by the phase voltage times number of phases. The line VS drawn parallel to OE represents the total motor power input with blocked rotor, and on the same scale VT represents the corresponding primary I^2R loss. Then ST represents the power input to the rotor at standstill, which, divided by the synchronous speed, gives the starting torque.

At any load point A , OA is the primary current, NA the secondary current, and AF the motor power input. The motor output power is AB , the torque X (synchronous speed) is AC , the secondary I^2R loss is BC , primary I^2R loss CD , and no-load copper loss plus core loss DF . The maximum power-factor point is P , located by drawing a tangent to the circle from O . The maximum output and maximum torque points are similarly located at Q and R by tangent lines parallel to NS and NT , respectively.

The diameter of the circle is equal to the voltage divided by the standstill reactance or to the blocked-rotor current value on the assumption of zero resistance in both windings. The maximum torque of the motor, measured in kilowatts at synchronous speed, is equal to a little less than the radius of the circle multiplied by the voltage OE .

Equivalent Circuit. Figure 20-28 shows the polyphase motor circuit usually employed for accurate work. The advantages of this circuit over the circle-diagram method are that it facilitates the derivation of simple formulas, charts, or computer programs for calculating torque, power factor, and

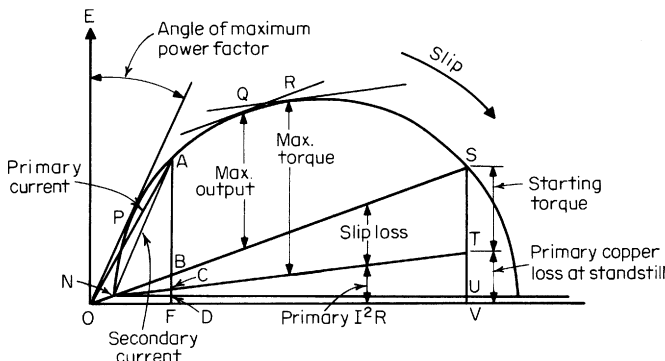


FIGURE 20-27 Circle diagram of polyphase induction motor.

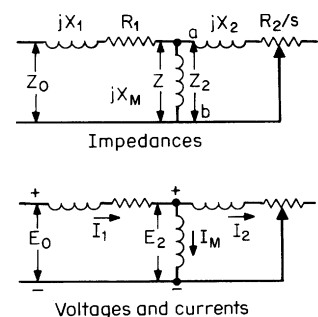


FIGURE 20-28 Equivalent circuit of polyphase induction motor.

TABLE 20-2 Formulas for Calculating Circuit Constants from Test Data for 3-Phase Motors

$X = \frac{f}{f_l} \sqrt{\frac{V^2}{3f^2} - \left(\frac{W}{3f^2}\right)}$	(see text)
$X_1 = X_2 = 0.5X$	for single squirrel-cage or wound-rotor motors
$X_1 = 0.4X \text{ and } X_2 = 0.6X$	for low-starting-current motors
$W_H + W_F = W_{RL} - 3I_M^2 R_1$	(see text)
W_s	(see text)
$X_M = \frac{E_0}{I_M} - X_1$	

other motor characteristics and that it enables impedance changes due to saturation or multiple squirrel cages to be readily taken into account.

Formulas for calculating the constants from test data are given in Table 20-2, and their definitions are given in Table 20-3.

Inspection of the circuit reveals several simple relationships which are useful for estimating purposes. The maximum current occurs at standstill and is somewhat less than E/X . Maximum torque occurs when $s = R_2/X$, approximately, at which point the current is roughly 70% of the standstill current.

TABLE 20-3 Definitions of Equivalent-Circuit Constants

Unless otherwise noted, all quantities except watts, torque, and power output are per phase for 2-phase motors and per phase Y for 3-phase motors:

E_0 = impressed voltage (volts) = line voltage $\div \sqrt{3}$ for 3-phase motors

I_1 = primary current (amperes)

I_2 = secondary current in primary terms (amperes)

I_M = magnetizing current (amperes)

R_1 = primary resistance (ohms)

R_2 = secondary resistance in primary terms (ohms)

R_0 = resistance at primary terminals (ohms)

X_1 = primary leakage reactance (ohms)

X_2 = secondary leakage reactance (ohms)

$\bar{X} = X_1 + X_2$

X_0 = reactance at primary terminals (ohms)

X_M = magnetizing reactance (ohms)

Z_1 = primary impedance (ohms)

Z_2 = secondary impedance in primary terms (ohms)

Z_0 = impedance at primary terminals (ohms)

Z = combined secondary and magnetizing impedance (ohms)

s = slip (expressed as a fraction of synchronous speed)

N = synchronous speed (revolutions per minute)

m = number of phases

f = rated frequency (hertz)

f_l = frequency used in locked-rotor test

T = torque (foot-pounds)

W_0 = watts input

W_H = core loss (watts)

W_F = friction and windage (watts)

W_{RL} = running light watts input

W_s = stray-load loss (watts)

Hence, the maximum torque is approximately equal to $E^2/2X$. This gives the basic rule that the percent maximum torque of a low-slip polyphase motor at a constant impressed voltage is about half the percent starting current.

By choosing the value of R_2 , the slip at which maximum torque occurs can be fixed at any desired value. The maximum-torque value itself is affected, not by changes in R_2 , but only by changes in X and to a slight degree by changes in X_M .

The magnetizing reactance X_M is usually 8 or more times as great as X , while R_1 and R_2 are usually much smaller than X , except in the case of special motors designed for frequent-starting service.

The equivalent circuit of Fig. 20-28 shows that the total power P_{g1} transferred across the air gap from the stator is

$$P_{g1} = mI_2^2 \frac{R_2}{s} \quad (20-14)$$

The total rotor copper loss is evidently

$$\text{Rotor copper loss} = mI_2^2 R_2 \quad (20-15)$$

The internal mechanical power P developed by the motor is therefore

$$\begin{aligned} P &= P_{g1} - \text{rotor copper loss} = mI_2^2 \frac{R_2}{s} - mI_2^2 R_2 \\ &= mI_2^2 R_2 \frac{1-s}{s} \\ &= (1-s)P_{g1} \end{aligned} \quad (20-16)$$

We see, then, that of the total power delivered to the rotor, the fraction $1-s$ is converted to mechanical power and the fraction s is dissipated as rotor-circuit copper loss. The internal mechanical power per stator phase is equal to the power absorbed by the resistance $R_2(1-s)/s$. The internal electromagnetic torque T corresponding to the internal power P can be obtained by recalling that mechanical power equals torque times angular velocity. Thus, when ω_s is the synchronous angular velocity of the rotor in mechanical radians per second

$$P = (1-s)\omega_s T \quad (20-17)$$

with T in newton-meters. By use of Eq. (20-16)

$$T = \frac{1}{\omega_s} mI_2^2 \frac{R_2}{s} \quad (20-18)$$

For T in foot-pounds and N_s in revolutions per minute

$$T = \frac{7.04}{N_s} mI_2^2 \frac{R_2}{s} \quad (20-19)$$

Torque and Power. Considerable simplification results from application of Thévenin's network theorem to the induction-motor equivalent circuit. Thévenin's theorem permits the replacement of any network of linear circuit elements and constant phasor voltage sources, as viewed from two terminals by a single phasor voltage source E in series with a single impedance Z . The voltage E is that appearing across terminals a and b of the original network when these terminals are open-circuited; the impedance Z is that viewed from the same terminals when all voltage sources within the network are short-circuited. For application to the induction-motor equivalent circuit, points a and b are taken as those so designated in Fig. 20-28. The equivalent circuit then assumes the forms given in Fig. 20-29. So far as phenomena to the right of points a and b are concerned, the circuits of Figs. 20-28 and 20-29 are identical when the voltage V_{1a} and the impedance $R_1 + jX_1$ have the proper values. According to

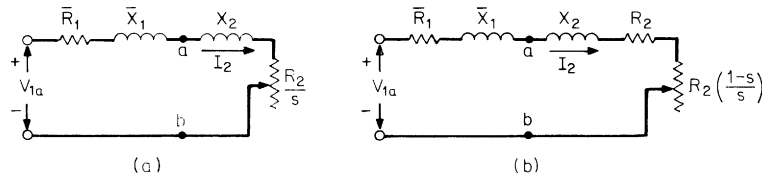


FIGURE 20-29 Induction-motor equivalent circuit simplified by Thévenin's theorem.

Thévenin's theorem, the equivalent source voltage V_{1a} is the voltage that would appear across terminals a and b of Fig. 20-28 with the rotor circuits open and is

$$V_{1a} = E_0 - I_0 (R_1 + jX_1) = E_0 \frac{jX_M}{R_1 + jX_{11}} \quad (20-20)$$

where I_M is the zero-load exciting current and

$$X_{11} = X_1 + X_M$$

is the self-reactance of the stator per phase and very nearly equals the reactive component of the zero-load motor impedance. For most induction motors, negligible error results from neglecting the stator resistance in Eq. (20-20). The Thévenin equivalent stator impedance $R_1 + jX_1$ is the impedance between terminals a and b of Fig. 20-28, viewed toward the source with the source voltage short-circuited, and therefore is

$$\bar{R}_1 + j\bar{X}_1 = R_1 + jX_1 \quad \text{in parallel with} \quad jX_M$$

From the Thévenin equivalent circuit (Fig. 20-29) and the torque expression (Eq. 20-18), it can be seen that

$$T = \frac{1}{\omega_s} \frac{mV_{1a}^2(R_2/s)}{(\bar{R}_1 + R_2/s)^2 + (\bar{X}_1 + X_2)^2} \quad (20-21)$$

The slip at maximum torque, $s_{\max T}$, is obtained by differentiating Eq. (20-21) with respect to s and equating to zero:

$$s_{\max T} = \frac{R_2}{\sqrt{\bar{R}_1^2 + (\bar{X}_1 + X_2)^2}}$$

The corresponding maximum torque is

$$T_{\max} = \frac{1}{\omega_s} \frac{0.5mV_{1a}^2}{\bar{R}_1 + \sqrt{\bar{R}_1^2 + (\bar{X}_1 + X_2)^2}}$$

20.4.2 Testing of Polyphase Induction Machines

Proof of guaranteed performance, the determination of torque or efficiency of driven machines, and the evaluation of design changes are some of the purposes that require accurate tests of induction machines. Normally, running-light, locked-rotor, resistance, and dielectric tests only are made on standard motors. Input-output tests or segregated-loss tests are made when accurate efficiency determination is required. The inconvenience of making input-output tests and the inaccuracies inherent in any method which determines the losses as a small difference between two large quantities make the segregated-loss methods of test preferable in many cases. Such tests are especially necessary when actual performance under the varying conditions of service is to be determined from a

limited number of factory or laboratory test runs. Experience has shown that the equivalent-circuit method of calculation enables accurate predictions of efficiency and other performance data to be made, provided the circuit “constants” are determined in advance by careful tests.

The IEEE Test Code for Induction Machines¹ gives authoritative procedures for conducting all usual tests, and many of the data contained in the following sections are derived from this source.

Running-Light Test. The motor is run at no load with normal frequency and voltage applied, until the watts input becomes constant. On slip-ring motors, the brushes are short-circuited. Readings of amperes and watts are taken at one or more values of impressed voltage, with rated frequency maintained. Accurately balanced phase voltages and a sine-wave form of voltage are necessary for good results, requiring operation of the test alternator and transformers well below magnetic saturation. The watts input at rated voltage will be the sum of the friction and windage, core loss, and no-load primary I^2R loss. Subtracting the primary I^2R loss at the temperature of test from the input gives the sum of the friction and windage and core loss. Segregation of the core loss from the windage and friction is not necessary for normal efficiency or other rated-voltage performance calculations. However, the segregation can be made, if desired, by taking amperes and watts input readings, at rated frequency, at different voltages varying from 125% of normal down to about 15% voltage, or the point of minimum current. Plotting the input watts, less primary I^2R , against the square of the voltage and extrapolating the lower part of the curve in a straight line to intercept the zero-voltage axis determines the friction and windage. Typical data of such a test are shown in Fig. 20-30.

The value of the magnetizing reactance X_M in Fig. 20-28 is determined from the no-load current at rated voltage I_0 by using the value of primary leakage X_1 determined from locked-rotor test data.

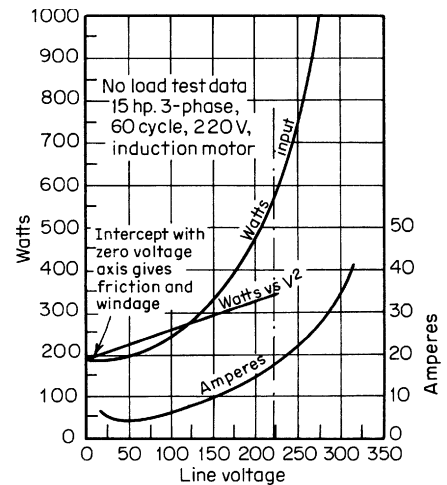


FIGURE 20-30 No-load excitation curves.

Locked-Rotor Test. The motor is blocked so it cannot rotate; a reduced voltage of rated frequency is applied to the terminals; and readings of volts, watts, and amperes are taken. Readings should be taken quickly, and the temperature of the windings should be observed before and after the test to minimize errors due to changing resistance values. In the case of machines with closed-slot rotors or very small air gaps, magnetic saturation of the leakage paths will occur, and it may be desirable to take readings at half or full voltage to establish the actual value of starting current. Equivalent-circuit performance calculations, however, should be based on data taken at approximately rated current.

When only low-voltage test data are available, the locked-rotor current at higher voltages can be estimated by the formula

$$I = \frac{V - V_0}{V_t - V_0} I_t \quad (20-22)$$

where V_t, I_t = test values of voltage and locked-rotor current; V, I = corresponding values at a different voltage; and V_0 = intercept of test current-voltage curve with zero-voltage axis, obtained by extrapolating the test curve as a straight line through points in the approximate range of 50% to 200% current. V_0 represents the voltage due to flux of saturation density crossing closed slot bridges and similar leakage flux paths.

The motor impedance per phase is determined from the volts, amperes, and watts readings. The total resistance component for a 3-phase motor is

$$R = \frac{W}{3I^2} \quad \Omega/\text{phase} \quad Y \quad (20-23)$$

and the reactance component is

$$X = \sqrt{\frac{V_L^2}{3I^2} - R^2} \quad \Omega/\text{phase} \quad Y \quad (20-24)$$

where W = watts input, I = line current, and V = voltage between lines.

Normally, the primary and secondary leakage-reactance values X_1 and X_2 are assumed equal, each having the value $X/2$.

The primary resistance is measured with direct current, a current about one-quarter of full-load value being preferably used, and readings being taken quickly to avoid errors due to temperature changes during the test. The primary resistance per phase Y is equal to one-half the resistance between any two terminals.

Subtracting the primary resistance at the temperature of test from the resistance component of the total impedance gives the effective secondary resistance at standstill. The starting torque may be calculated from this value by the equation

$$\text{Starting torque} = \frac{7.04KmI^2R_{2e}}{N_s} \quad \text{ft} \cdot \text{lb} \quad (20-25)$$

where I = amperes starting current per phase at specified voltage; m = number of phases; N_s = synchronous speed in r/min ; R_{2e} = resistance component of motor impedance, less primary resistance at temperature of test, in ohms per phase; K = an empirical constant, usually approximately 0.9, which allows for nonfundamental secondary losses.

In practice, it is usual to measure the torque produced, by means of a lever arm and scale, in which case Eq. (20-25) provides a useful check on the accuracy of the measurements.

In the case of deep-bar or double squirrel-cage motors, the effective secondary reactance at speed is materially higher than at standstill, owing to the progressive shifting of the secondary current from the low-reactance, high-resistance paths into the low-resistance, high-reactance paths as the secondary, or slip, frequency decreases. Hence, for accurate performance calculations, it is necessary to determine the motor reactance at low secondary frequency. If a low-frequency supply is available, the locked-rotor test may be repeated at 15 Hz, or at most 25 Hz, for a 60-Hz motor. Calculation of the low-frequency reactance by Eq. (20-24) and multiplying this by the ratio of the rated to the test frequency will give the proper value to use in operating performance calculations.

Alternatively, the reactance value at speed may be obtained by adding an amount ΔX to the reactance determined by full-frequency locked-rotor test. The value of ΔX is approximately

$$\Delta X = R_{2e} - R_2 \quad (20-26)$$

where R_2 = secondary resistance of full-load slip, determined by the slip test.

Slip Test. Whenever feasible, a current-slip curve should be taken under actual load conditions, with rated voltage and frequency maintained at the motor terminals. Measurements at a few points in the neighborhood of full-load current are usually sufficient; but for slip-ring motors a wider range should be covered, owing to the variable resistance and should therefore be measured with a slip meter or stroboscopically. The slip-meter method makes use of a revolution counter differentially geared to the motor under test and to a small synchronous motor driven from the same power supply at the same synchronous speed. Care must be taken to correct the observed values of slip for the

difference between the test temperature and the standard value of 75°C or the temperature attained in a full-load heat run with an ambient temperature of 25°C.

In practice, the value of current corresponding to an assumed value of R_2/s is calculated exactly by the equivalent circuit; the corresponding value of s is read off the slip-current curve; and the true value of R_2 is obtained by multiplying R_2/s by this value of s . However, R_2 may be approximately determined as follows:

Very roughly, the secondary resistance is equal to

$$R_2 = 1.1 \frac{E \cdot s}{I_1} \quad \text{approx} \cdot \Omega/\text{phase} \quad (20-27)$$

where E = terminal voltage per phase, s = ratio of revolutions per minute of slip to synchronous speed, and I_1 = observed phase current.

The coefficient 1.1 varies over a range of about 1 to 1.2, depending on the motor characteristics and the value of the test load.

In case direct slip measurements are not practicable, the value of R_2 determined by Eq. (20-23) in a low-frequency locked-rotor test may be used. Or, in the case of a wound rotor, the actual resistance between slip rings may be measured and multiplied by the square of the ratio of primary to secondary volts to obtain the resistance referred to primary. The voltage ratio is obtained by measurement of primary and secondary voltages at standstill with the slip rings open-circuited. Averages of several rotor positions are taken to avoid errors due to possible unbalance.

Stray-Load Loss Tests. Stray-load losses, W_s , are defined as the excess of the total measured losses above the sum of the friction and windage, core, and copper losses calculated for the conditions of load from the no-load tests described above. These extra losses are made up chiefly of high-frequency core losses and rotor I^2R losses caused by the pulsations of the leakage-reactance fluxes produced by load currents. While the stray-load losses may be determined by direct input-output tests with a dynamometer or calibrated driving motor, the result is a small difference between two large quantities and so accuracy is very difficult to obtain. Whenever such tests are made, it is desirable to repeat them with the direction of power flow reversed, so the measurement errors may be substantially canceled out.

There are several ways of determining the stray-load loss by separate loss measurements, but the procedure is fairly complex and must be carefully done if accurate results are to be obtained. These are described in the *IEEE Test Code for Polyphase Induction Machines*.

Performance Calculations. From the foregoing tests, all the circuit constants may be determined, enabling the equivalent-circuit calculations to be carried out. To facilitate this, the formulas for calculating the constants as defined in Table 20-3 are collected in Table 20-2.

The procedure in making performance calculations based on test data is first to divide E_0 by the appropriate expected value of normal current, an arbitrary value of R_2/s being thus obtained. With this value and the known circuit constants, calculations are carried through for one point, determining the actual value of I . By entering the test slip-current curve, the true value of s is found, and from this and R_2/s , R_2 is calculated. All the circuit constants are then known, whence the efficiency, power factor, torque, etc., are determined. Additional points are calculated with different values of s , covering the desired range of loads, and the exact characteristics are taken off curves plotted from the calculated results.

If values of torque, current, etc., are desired for considerable overloads or throughout the accelerating range, the value of R_2 and X should be modified to allow for magnetic saturation and eddy currents. Curves of reactance against current obtained by locked-rotor tests over the desired range of values and values of R_{2e} and corresponding values of ΔX obtained by locked-rotor tests at different frequencies are desirable for this purpose, especially in cases of closed-slot or double squirrel-cage rotors.

Temperature Tests. Temperature tests are made to determine the temperature rise of insulated windings under load conditions. ANSI Standards specify a limiting temperature for continuous-rated

machines of 50°C by thermometer or 60°C by either the resistance- or the embedded-detector method for Class A insulating materials and corresponding values of 70°C by thermometer and 80°C by resistance or embedded detector for Class B insulation. Usually, the temperature is measured by mercury thermometers or thermocouples applied to the hottest accessible parts of the core and windings in several different locations. A small amount of putty is used to shield thermometer bulbs from the surrounding air, and care is taken to avoid external air currents, varying ambient temperatures, or other factors, which may introduce errors.

The preferred method of making a full-load temperature test is to maintain nameplate voltage, current, and frequency until the temperature becomes constant, readings being taken every half hour. When constant temperature is reached, the motor is stopped as quickly as possible and additional thermometers are applied to the rotating parts as soon as these have come to rest. The maximum permissible time of stopping is 1 min for machines of less than 50 kW rating, 2 min for 50 to 200 kW ratings, and 3 min for machines larger than 200 kW. The winding temperatures usually increase after shutdown; so readings must be recorded at frequent intervals until definitely falling temperatures are observed. The highest temperature reached at any time during the test is taken as the correct value. If the temperatures fall continuously after shutdown, a curve should be plotted of temperature versus time and extrapolated back to the moment of shutdown.

For protected-type or totally enclosed machines, it is often preferable to determine the temperature by the rise-of-resistance method. In this case, the “cold” resistance of the winding is measured at a known temperature, usually after the machine has been standing overnight at a uniform room temperature; and the “hot” resistance is measured immediately after shutdown. The hot resistance is taken as the highest value obtained after shutdown or is extrapolated back to the moment of shutdown if the resistance falls continuously.

The temperature is then calculated from the following formula:

$$T = \frac{R_T(234.5 + t)}{R_t} - 234.5 \quad (20-28)$$

where T = winding temperature when R_T was measured, R_T = hot resistance, R_t = cold resistance, and t = winding temperature when R_t was measured.

Reference on Polyphase Induction Machine Testing

1. *American Standard Test Code for Polyphase Induction Motors and Generators*, USASC 50.20-1954.

20.4.3 Characteristics of Polyphase Induction Motors

Types. All polyphase induction motors may be classified as squirrel-cage or wound-rotor, and may be of the single-speed or multispeed type. Squirrel-cage motors are further classified by NEMA¹ for torque-speed and current-speed curves as Designs A, B, C, and D, and by Code designations from A to V for locked-rotor kVA/hp. For all induction motors, the allowable temperature rises and insulation systems are designated by classes A, B, F, and H. Finally, the mechanical dimensions are designated by frame sizes, and in enclosures from dripproof to totally enclosed with various types of ventilation. Both squirrel-cage and wound-rotor motors may be of the single-speed or multispeed type.

Based upon efficiency, motors are also classified as standard and energy-efficient motors. Several manufacturers have developed product lines of energy-efficient motors under various trade names. Some of these trade names are XE-Energy Efficient (Reliance Electric Co.), Energy Efficient Corro-Duty (US Electric Motors), and PE-21 Plus (Siemens).

Squirrel-Cage Motors. All integral-horsepower induction-motor design categories can mechanically withstand the magnetic stresses and locked-rotor torques of full-voltage line starting. The torque- and current-speed curves for Design A, B, C, and D squirrel-cage motors are shown in Figs. 20-31 to 20-33. Design B motors are most widely used; they have starting-torque and line-starting current characteristics suitable for most power systems. Design C and D motors have higher torque than Class B motors. For all design motors, the percentage torques tend to decline with

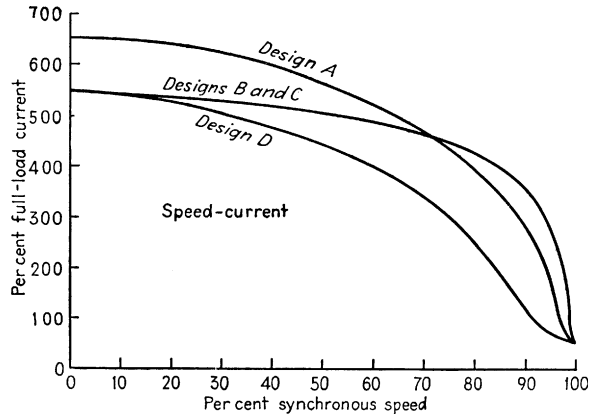


FIGURE 20-31 Typical speed-current curves for squirrel-cage induction motors.

increased hp rating cost. Typical load conditions and applications for Design A, B, C, and D motors are given in Table 20-4.

Wound-Rotor Motors. An insulated winding, usually 3 phase, is provided on the rotor; the terminal of each phase is connected to a slip ring on the shaft. The stationary brushes, which bear on the slip rings, are connected to external adjustable resistance or solid-state converters by which power can be removed from, or injected into, the rotor to adjust the speed. Speed-torque and speed-current curves for a typical wound-rotor motor for various amounts of external resistance are shown in Fig. 20-34. The numbers on the curves refer to the percent external resistance; 100% resistance gives rated torque at standstill. The use of solid-state converters in a modified Kraämer system is described later in reference to synchronous motor starting.

Wound-rotor motors are normally started with relatively high external resistance and this resistance is short-circuited in steps as the motor comes up to speed. Liquid rheostats are used in the higher ratings. This procedure allows the motor to deliver high-starting and accelerating torques, yet draw relatively light line current. Furthermore, most of the rotor-circuit losses during acceleration are dissipated in the external resistor rather than within the motor.

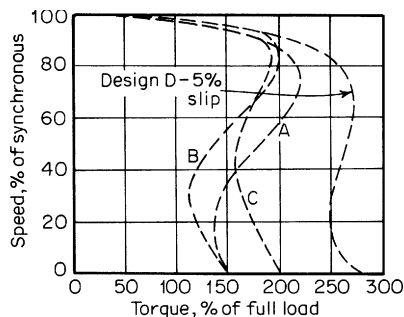


FIGURE 20-32 Speed-torque curves for typical NEMA standard Design A, B, C, and D squirrel-cage motors.

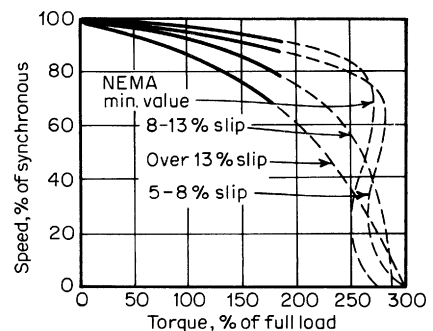


FIGURE 20-33 Speed-torque relationship for Design D squirrel-cage motors.

TABLE 20-4 3-Phase Electric Motor Selection Chart

For this type of equipment	Requiring these torques		With these load characteristics	Type and description
	Starting	Max. running		
Water supply pumps	100–150% of full-load torque	200–250% of full-load torque	Continuous operation, constant speed, high speed (over 720 r/min), easy starting; subject to short time overloads; good speed regulation	<i>Energy-efficient</i> : NEMA Design B, normal torques; normal starting current; can be used with variable-frequency variable-voltage inverters; higher efficiency than standard Design B motors
Industrial and chemical pumps				
Cooling towers				
Air-handling equipment				
Compressors				
Conveyors				
Process machinery				
Petroleum and chemical process equipment				
Centrifugal pumps				
Blower and fans				
Drilling machines				
Grinders				
Lathes				
Compressors				
Conveyors				
Reciprocating pumps				
Stokers				
Compressors				
Crushers				
Ball and rod mills				
Punch presses				
Cranes				
Hoists				
Press brakes				
Shears				
Oil-well pumps				
Centrifugals				

Blowers	Some require low torque; others require several times full-load torque	200% of full-load torque at each speed	Speed selection is desired, and two, three, or four fixed speeds are sufficient; starting torque can be low on blowers to high on conveyors; metal-cutting machines are usually constant hp; friction loads (conveyors) are usually constant torque; fluid or air loads (blowers) are variable torque	<i>Multispeed</i> : general normal torque on dominant winding or speed; consequent pole windings or separate windings for each speed; based on load requirement, can be constant horsepower, constant torque, variable torque
Fans				
Mixing machines				
Conveyors				
Pumps				
Crushers	Can provide torque up to maximum torque at standstill	200–300% of full-load torque	Loads that require very high starting torque with low starting current; required speed adjustment over limited range (2 to 1); torque control during acceleration or controlled acceleration	<i>Wound-rotor</i> : requires rotor control system to provide desired characteristic; control may be resistors or reactors or fixed-frequency inverters in the secondary (rotor) circuit; actual load speed depends on setting of rotor control
Conveyors				
Bending rolls				
Ball and rod mills				
Centrifugal blowers				
Pumps				
Printing presses				
Cranes and hoists				
Centrifugals				

Source: Andreas, J. C., *Energy Efficient Electric Motors*, 2d ed., New York, Marcel Dekker, 1992.

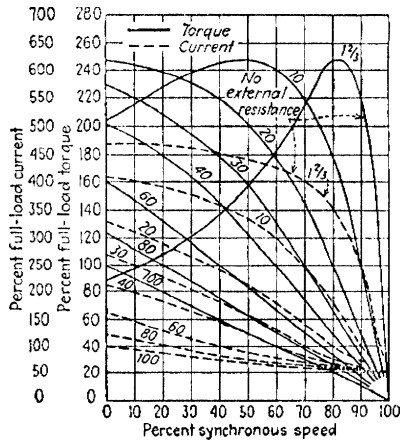


FIGURE 20-34 Speed-torque and speed-current curves of typical wound-rotor induction motor.

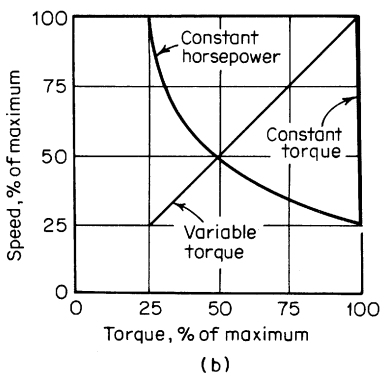
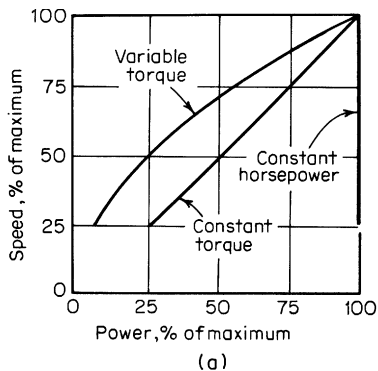


FIGURE 20-35 Basic load characteristics of multispeed motors having a 4:1 maximum speed ratio: (a) power; (b) torque.

The curves of Fig. 20-34 indicate that the external resistance reduces the speed at which the motor will operate with a given load torque. For any one value of external resistance, the motor has varying speed characteristics; any change in load results in a considerable change in speed. The lower the operating speed, the more pronounced the effect, so that it is usually not feasible to operate at less than 50% of full speed by this method. Furthermore, because the power loss in the rotor and external resistor is proportional to the slip, the efficiency is reduced in direct proportion to the speed reduction.

Breakdown torque is given by NEMA in MG1-12.40. Secondary data, including open-circuit slip-ring voltage and short-circuit slip-ring current, at standstill, are given in MG1-1034.

Slip-ring motors with external resistance are used as adjustable-speed motors from 50% to full speed for loads such as pumps and fans. They are used over the full speed range for hoists, elevators, and ski lifts. In addition, slip-ring motors are used to provide high starting and accelerating torque with low current for centrifuges, crushers, pulverizers, and other high-inertia loads. Solid-state ac and dc drives have replaced wound-rotor motors in many applications.

Multiple-Speed Squirrel-Cage Motors. Multispeed squirrel-cage motors may be of the single-winding or two-winding type. The former have a stator winding, which can be connected to give either one of two speeds having a ratio of 2:1. The method of connection is usually furnished by the controller manufacturer. The frame of the two-speed single-winding motor is about the same as that of the single-speed motor. The two-winding motor has two separate stator windings, which can be wound for any number of poles so that any two synchronous speeds can be obtained. In addition one or both of the stator windings may be arranged for reconnection as in a single-winding motor, giving a total of three or four speeds, but the two speeds obtained on a single winding must have a ratio of 2:1. Thus, a four-speed two-winding motor might have speeds of 1800, 900, 1200, and 600 r/min.

Multispeed motors are designed as (1) variable-torque motors, (2) constant-torque motors, and (3) constant-horsepower motors. The rated torque at four speed points for each type is shown in Fig. 20-35. Variable-torque motors have 1200/600 r/min, and are used on loads, such as in centrifugal pumps and fans whose horsepower requirement decreases more rapidly than the square of the reduction in speed. Constant-torque motors have horsepower ratings at each speed directly proportional to the speed, for example, 20/10 hp and 1200/600 r/min, and are used on conveyors, mixers, reciprocating compressors, printing presses, and other “constant-torque” loads. Constant-horsepower motors have the

TABLE 20-5 Temperature Rise for Single-Phase and Polyphase Induction Motors

	Class of insulation system			
	A	B	F	H
Integral horsepower				
All motors with 1.15 service factor or higher	70°C	90°C	115°C	—
Totally enclosed fan-cooled motors	60°C	80°C	105°C	125°C
Totally enclosed nonventilated motors	65°C	85°C	110°C	135°C
Motors with encapsulated windings, 1.0 service factor	65°C	85°C	110°C	—
All other motors	60°C	80°C	105°C	125°C
Fractional horsepower				
Open motors with 1.15 service factor or higher	70°C	90°C	115°C	—
Totally enclosed nonventilated and fan-cooled motors	65°C	85°C	110°C	135°C
Any motor in frame smaller than 42 frame	65°C	85°C	110°C	135°C
All other open motors	60°C	80°C	105°C	125°C

Note: Based on ambient temperature of 40°C, 3300-ft altitude. Temperature determined by the resistance method.

same horsepower rating at all speeds. They are used principally on machine tools, such as lathes, boring mills, planers, and radial drills. Multispeed motors of the constant-torque or variable-torque type are usually given a standard horsepower rating at the top speed but may have odd horsepower ratings at the lower speeds, since the latter are fixed by the speed ratios.

Temperature Rise. Temperature rise is no longer used as a rating method. Instead the manufacturer specifies the ambient temperature and the insulation class. The temperature rise will not exceed the limit for the insulation system when the motor is loaded to its rating or to its service factor load. The temperature rise limits are given in Table 20-5.

The temperature attained by squirrel-cage windings, cores, and mechanical parts shall not injure the machine in any respect. Temperatures shall be determined in accordance with the *IEEE Test Procedures*, Publication Nos. 112A and 114. For Class F and H insulation systems, special consideration shall be given to the bearings and lubrication.

The temperature rise for motors operating at any other ambient temperature T_a than 40°C shall not exceed the values

For items *a, b, e, f, i*: temperature rise = $0.9(T_h - T_a)$

For items *c, d, g, h*: temperature rise = $0.965(T_h - T_a)$

where T_h , the hot-spot temperature, is given by the following table:

Preferred values of ambient temperature above 40°C are 50°C, 65°C, 90°C, 115°C.

The time ratings for single-phase and polyphase induction motors shall be 5, 15, 30, 60 min, and continuous. All short-time ratings are based upon a load test which shall commence when the windings and parts of the motor are within 5°C of the ambient temperature.

Class	Items <i>a</i> and <i>f</i>	All other items
A	115°C	105°C
B	140°C	130°C
F	165°C	155°C
H		180°C

Service Factor. General-purpose fractional- and integral-horsepower motors are given a “service factor,” which allows the motor to deliver greater than rated horsepower, without damaging its insulation system. The motor is operated at rated voltage and frequency. The standard service factors are 1.4 for motors rated $\frac{1}{20}$ to $\frac{1}{8}$ hp; 1.35 for $\frac{1}{6}$ to $\frac{1}{3}$ hp; 1.25 for $\frac{1}{2}$ hp to the frame size for 1 hp at 3600 r/min. For all larger motors through 200 hp, the service factor is 1.15. For 250 to 500 hp, the service factor is 1.0.

20-38 SECTION TWENTY

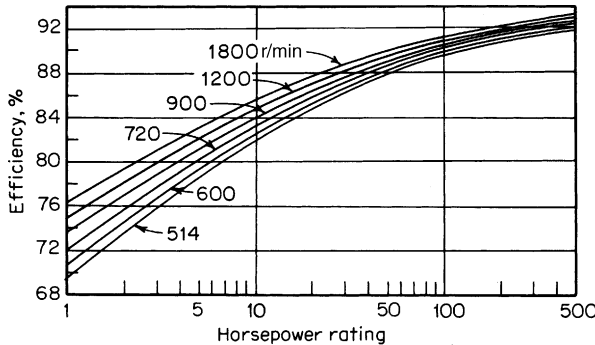


FIGURE 20-36 Typical full-load efficiencies of Design B squirrel-cage motors.

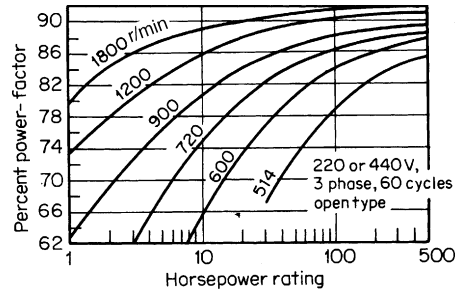


FIGURE 20-37 Typical full-load power factors of Design B squirrel-cage motors.

Efficiency and Power Factor. Typical full-load efficiencies and power factors of standard Design B squirrel cage induction motors are given in Figs. 20-36, and 20-37, respectively. The efficiencies of Design A motors are generally slightly lower, and those of Design D motors considerably lower. The power factors of Design A squirrel-cage induction motors are slightly higher, and those of Design C are slightly lower. Energy-efficient motors are those whose design is optimized to reduce losses. Comparative efficiencies of standard and energy-efficient motors of NEMA Design B are shown in Fig. 20-38.

Full-Load Current. With the efficiency and power factor of a 3-phase motor known, its full-load current may be calculated from the formula

$$\text{Full-load current} = \frac{746 \times \text{hp rating}}{1.73 \times \text{efficiency} \times \text{pf} \times \text{voltage}} \quad (20-29)$$

where the efficiency and power factor are expressed as decimals.

Torques and Starting Currents. Starting and breakdown torques of common Design A, B, and C squirrel-cage induction motors are given in Table 20-6. Relative values for other classes of squirrel-cage

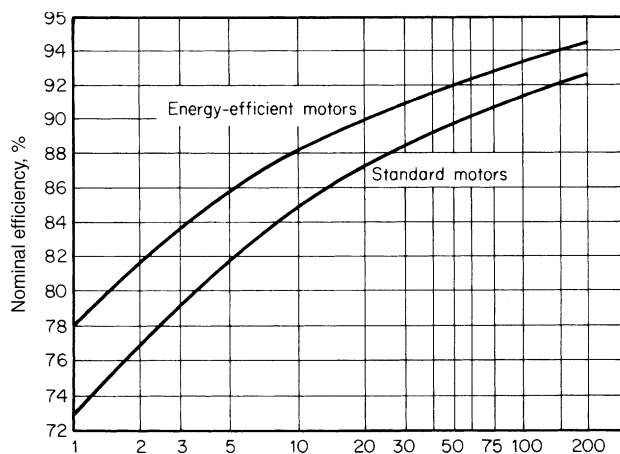


FIGURE 20-38 Nominal efficiencies for NEMA Design B, 4-pole motors, 1800 r/min; standard vs. energy-efficient motors.

TABLE 20-6 Torques-Polyphase Induction Motors
(Percent of full-load torque)

Rpm	3,600			1,800			1,200			900			720		
	LR	AB	BD	LR	AB	BD	LR	AB	BD	LR	AB	BD	LR	AB	BD
Torque Design															
1/2 hp	...	...	...	...	...	...	...	...	...	150	...	...	150	...	200
3/4 hp	...	...	...	...	...	...	...	...	...	150	...	...	150	...	200
1 hp	...	...	...	...	...	...	...	...	...	150	...	...	150	...	200
1 1/2 hp	175	275	275	...	265	300	...	175	...	150	...	...	150	...	200
2 hp	175	250	250	...	250	275	...	175	...	150	...	...	150	...	200
3 hp	175	250	250	...	250	275	...	175	...	150	...	...	145	...	200
5 hp	150	225	225	...	185	225	...	175	...	150	...	...	135	...	200
7 1/2 hp	150	215	215	...	175	215	...	160	...	130	...	...	130	...	200
10 hp	150	200	200	...	175	200	...	150	...	125	...	...	120	...	200
15 hp	150	200	200	...	165	200	...	140	...	125	...	...	120	...	200
20 hp	150	200	200	...	150	200	...	135	...	125	...	...	120	...	200
25 hp	150	200	200	...	150	200	...	135	...	125	...	...	120	...	200
30 hp	150	200	200	...	150	200	...	135	...	125	...	...	120	...	200
40-200 hp	—*	200	200	...	—*	200	...	—*	...	125	...	...	120	...	200

*Progressively lower values for these larger ratings.

Note: LR = locked-rotor torque; BD = breakdown torque; A, B, and C refer to Design A, etc.

TABLE 20-7 Locked-Rotor kVA for Code-Letter Motors

Code letter*	kVa per hp, with locked rotor	Code letter*	kVa per hp with locked rotor
A	0–3.14	L	9.0–9.99
B	3.15–3.54	M	10.0–11.19
C	3.55–3.99	N	11.2–12.49
D	4.0–4.49	P	12.5–13.99
E	4.5–4.99	R	14.0–15.99
F	5.0–5.59	S	16.0–17.99
G	5.6–6.29	T	18.0–19.99
H	6.3–7.09	U	20.0–22.39
J	7.1–7.99	V	22.4 and up
K	8.0–8.99		

*National Electrical Code.

motors are indicated by the curves of Fig. 20-33. The minimum breakdown torque for wound-rotor motors is 200% of full-load torque. As indicated by the curves of Fig. 20-34, the starting torque and starting current of wound-rotor motors vary with the amount of external resistance in the secondary circuit.

The starting kVA of a squirrel-cage motor is indicated by a code letter stamped on the nameplate. Table 20-7 gives the corresponding kVA for each code letter, and the locked-rotor current can be determined from

$$\text{Locked-rotor current} = \frac{\text{kVA/hp} \times \text{hp} \times 1000}{k \times \text{line volts}} \quad (20-30)$$

where $k = 1$ for single-phase, and $k = 1.73$ for 3-phase.

Maximum locked-rotor current for Design B, C, and D 3-phase motors has been standardized as shown in Table 20-8 for 230 V. The starting current for motors designed for other voltages is inversely proportional to the voltage.

Starting Methods. Wound-rotor motors are invariably started on full voltage but with external resistance in the secondary circuit. Ordinarily sufficient resistance is provided to give 100% torque at standstill, which means that 100% current will be drawn from the line. If a higher torque is required to start the load, less external resistance must be used, and the current drawn is proportionately higher. As the motor accelerates, the external secondary resistance is short-circuited in one or more steps.

The locked-rotor values in Table 20-8 are generally recognized as the minimum needed by motor designers to obtain the required torque characteristics for general-purpose motors. Squirrel-cage motors with these values are usually acceptable for full-voltage starting on power lines and also on combined light and power secondaries of 208 or 230 V, if manually controlled (infrequently started).

TABLE 20-8 Locked-Rotor Current for 3-Phase Motors at 230 V

Rated horsepower	Classes B, C, D, amperes	Rated horsepower	Classes B, C, D, amperes	Rated horsepower	Classes B, C, D, amperes	Rated horsepower	Classes B, C, D, amperes	Rated horsepower	Class B amperes
1	30	7½	127	30	435	100	1450	250	3650
1½	40	10	162	40	580	125	1815	300	4400
2	50	15	232	50	725	150	2170	350	5100
3	64	20	290	60	870	200	2900	400	5800
5	92	25	365	75	1085			450	6500
								500	7250

In the case of automatically controlled (frequently started) equipment, with 208- or 230-V motors supplied from combined light and power secondaries, current-reducing starters to reduce the current to about 65% of these values may be required, unless consultation with the power company indicates that the available system capacity will permit use of full-voltage starting. In any case, consultations with the power company for motor applications above 25 hp are advisable.

Autotransformer starters (compensators) are the most popular of any reduced-voltage type. They have the advantage that the ratio of torque developed by the motor to the current drawn from the line remains substantially the same as for full-voltage starting. The motor torque and the current drawn from the line (neglecting the magnetizing current of the autotransformer) are both reduced in proportion to the square of the voltage impressed on the motor. The magnetizing current of the autotransformer generally does not exceed 25% of motor full-load current. Normally, the motor accelerates nearly to full speed on the reduced-voltage connection and is then transferred to full voltage. Since the circuit to the motor is opened and then immediately reclosed, a transient inrush of current occurs which may be of much greater magnitude than the current normally drawn by the motor at the speed at which the transfer is made. This transient inrush, however, is of such extremely short duration that it does not produce an objectionable voltage disturbance on the average power system. Standard autotransformer starters are provided with 65% and 80% voltage taps in sizes up to 50 hp and with 50%, 65%, and 80% voltage taps in the larger sizes.

"Part-winding" starting is being more widely used for reducing starting current. This involves arranging the stator winding so that, by use of adequate control devices, one part of the stator winding is first energized and subsequently the remainder of the winding is energized in one or more steps. The purpose is to reduce the initial values of the starting current drawn and/or the starting torque developed by the motor. The usual arrangement involves energizing one-half the stator winding on the first step, resulting in approximately 50% of normal locked-rotor torque and approximately 60% of normal locked-rotor current. While this torque may be insufficient to start the motor in some applications, it permits drawing full-winding starting current from the system in two increments. Another method is to connect two-thirds of the winding on the first step, by using a 4-pole contactor, in which case the motor should accelerate promptly to full speed. The remaining third of the winding is then connected by closing a second contactor with only two poles.²⁻⁴

Resistor-type reduced-voltage starters are sometimes used. They have the disadvantage that the current drawn from the line is reduced in direct ratio to the impressed voltage, while the torque developed by the motor is reduced as the square of this voltage. The resistor is short-circuited, either all at once or in steps, when the motor comes up to speed. The circuit for the motor is not broken in transferring to full voltage, as is the case with the autotransformer starter. These features make the resistor-type starter adapted for use where "increment-type" starting-current restrictions exist. With the resistor-type starter, the contactors, which short-circuit the resistors as well as the line contactors, must carry the full current of the motor, whereas in part-winding starting, the contactors for the two parts of the winding each carry only half the total current.

Reactor-type reduced-voltage starters are sometimes used on larger motors, most frequently on high-voltage motors (2300 V or above), where oil circuit breakers are necessary to provide sufficient current-interrupting capacity. In such cases, the reactor and starting circuit breaker are placed in the neutral of the motor. The breaker can then be of low-interrupting capacity, since the fault current at this point is limited by the reactance of the motor windings.

Wye-delta starting, though quite common abroad, is used in the United States primarily for refrigeration compressors. This starter consists of a switching arrangement that transfers the motor winding from Y for starting to Δ for running. The current drawn and the torque developed by the motor are thus reduced to only one-third their full voltage values. This very low torque, the extra contactors required, and the current inrush when the circuit is reclosed on Δ make this scheme less attractive than others.

Motors are frequently supplied from power systems consisting of complex networks for which calculation of the voltage drop would be difficult. The voltage drop may be estimated, however, if the short-circuit kVA is known at the point of power delivery.

When motor-starting kVA is drawn from a system, the voltage drop in percent of the initial voltage is approximately equal to 100 times the motor-starting kVA divided by the sum of this kVA and the short-circuit kVA. The motor-starting kVA used should be that drawn by the motor if the initial

system voltage is maintained. For example, if a 1000-hp motor has a starting kVA of 5000 at the initial system voltage and the system short-circuit kVA is 50,000, the voltage drop will be approximately

$$\frac{5000 \times 100}{(5000 + 50,000)} = 9\% \text{ of initial voltage}$$

In many systems, the short-circuit kVA varies over a wide range depending on the number of parallel lines in service, service interconnections, etc. While the highest short-circuit kVA is of interest for circuit interruption, the minimum short-circuit kVA should be used for voltage-drop calculations since it gives the highest value.

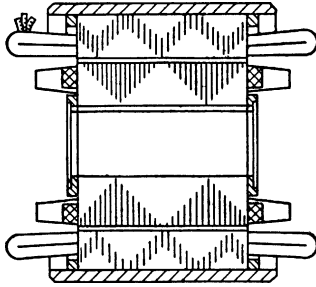


FIGURE 20-39 Cross section of shell-type motor.

Shell-Type Motors. These motors consist of stators and rotors only, without shafts, end shields, bearings, or conventional frame (Fig. 20-39). The rotors are mounted directly on a shaft of the driven machine, which must also include a suitable support for the stator and a ventilating arrangement. The motors are built with relatively small outside diameters but may be slightly longer than standard machines. Furthermore, horsepower ratings over a rather wide range are built in each frame diameter, the ratings for the different diameters overlapping slightly. Although a great many of the motors used are for operation at standard commercial frequencies giving speeds up to 3600 r/min (on 60 Hz), they are frequently supplied for operation at higher frequencies and correspondingly higher speeds. Frequencies up to 2000 Hz with a corresponding 2-pole motor speed of 120,000 r/min have been used, but the more common “high” frequencies range from

60 to 240 Hz, giving 2-pole motor speeds up to 14,400 r/min.

Shell-type motors are used principally on machine tools and woodworking machinery. Their relatively small physical size facilitates a compact design with maximum flexibility in arrangement of machine parts. The small diameter of the motors is of particular value, since it allows close spacing of spindle shafts.

The wide range of ratings available in each diameter reduces the cost of providing suitable mountings for the motors.

Motors of similar mechanical construction but with special insulation are used in hermetically sealed refrigeration and air-conditioning compressors, where the motor runs in an atmosphere of refrigerating gas. The insulation must neither harm nor be harmed by the refrigerant and, so that the refrigerant may be kept clean and dry, must not trap moisture or dirt.

Dimensions. NEMA has standardized mounting dimensions for various types of motors, those standardized for polyphase induction motors covering ratings from 1 to 125 hp (at 1800 r/min). For convenience each set of standardized dimensions has been assigned a frame number, and the various ratings of motors have been assigned frame numbers from the series. Any motor offered by a manufacturer having a frame number from this series will have the corresponding standardized mounting dimensions. These are listed in *NEMA Motor and Generator Standard*, Publ. MG1-1987.

References on Polyphase Induction Motors

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2. Alger, P. L., Ward, H. C., Jr., and Wright, F. H., Split-Winding Starting in 3-Phase Motors, *Trans. AIEE*, 1951, vol. 70, pt. 1, p. 867.
3. Alger, P. L., and Agacinsky, L., A New Method for Part-Winding Starting of Polyphase Motors, *Trans. AIEE, Power Apparatus and Systems*, Feb. 1956, no. 22, p. 1455.
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20.4.4 Single-Phase Induction Motors

General Theory. If one supply line to a polyphase induction motor is opened, the motor will not develop any starting torque, although if it is already operating, it will continue to run at slightly reduced speed, with a somewhat lower breakdown torque. The crux of the single-phase motor problem, therefore, is in providing auxiliary means for starting.

The magnetic field of a single-phase winding carrying alternating current may be represented as a phasor stationary in space but alternating in time, or as the sum of two equal and oppositely revolving field phasors, which are constant in magnitude. In a polyphase motor, the backward-revolving field phasors of the several phases cancel each other, and the forward-revolving ones add directly, giving a uniform revolving field. In the single-phase motor, means are provided to reduce the backward field, but this field has always some remaining magnitude (except at one particular load in the case of certain capacitor-run motors), and consequently a single-phase induction motor always has extra losses and a double-frequency pulsating torque not possessed by a polyphase motor.

A simple way to visualize the effects of this backward field is to consider that the forward- and backward-revolving fields are separately produced by the same stator current; that is, they are connected in series. Each field may then be treated as a separate polyphase induction motor, the forward field having a slip s with respect to the rotor, and the other a slip $2 - s$. At standstill, both values of slip are unity, and the two circuits are identical. At all times, the net torque developed is equal to the difference of the separate torques produced by the two fields. On this basis, the single-phase induction motor equivalent circuit is given by Fig. 20-40.

The values of R_1 , X_1 , R_2 , X_2 , and X_M are the impedance constants derived by measurements across the single-phase terminals. Since half the total air-gap impedance at standstill is due to each field, the magnetizing and secondary impedance values are divided by 2 to obtain the values corresponding to the separate fields.

Inspection of this circuit reveals several interesting properties of the motor. At full speed, s is very small, and the backward field appears as an external series impedance of $R_2/4 + j(X_2/2)$. The corresponding loss $I^2 R_2/4$ represents the power delivered to the rotor by the backward field. However, there is an equal loss due to the rotor's being driven forward at speed $1 - s$ against the backward-field torque; so the total loss caused by the backward field is $I^2 R_2/2$, approximately. Since the backward-field rotor currents occur at double-line frequency, any double squirrel-cage or deep-bar rotor design which had an increased resistance at high frequency would greatly increase the power losses, and such designs, therefore, are seldom used for single-phase motors. The breakdown torque of a single-phase motor may be approximately calculated for a polyphase induction motor, if the impedance of the backward-revolving field is considered as a series impedance added in the primary circuit of the polyphase motor. Hence, any increase in the secondary resistance of a single-phase motor actually reduces the breakdown torque and lowers the speed at which breakdown occurs.

Another interesting characteristic is the double-frequency torque pulsation. The double-frequency current in the rotor reacting on the slip-frequency forward magnetic field evidently produces a torque pulsation, even at no load. Physically, the no-load part of the pulsating torque provides the means for supplying and removing the magnetic field twice each cycle in the axis at right angles to the stator winding, and the additional part under load corresponds to the double-frequency pulsation of the single-phase power input to the rotor. To prevent objectionable transmitted vibration and noise from this cause, it is usual to mount single-phase machines on supports with torsional elasticity of some type, often rubber rings encircling the bearing housings in the case of fractional-horsepower motors.

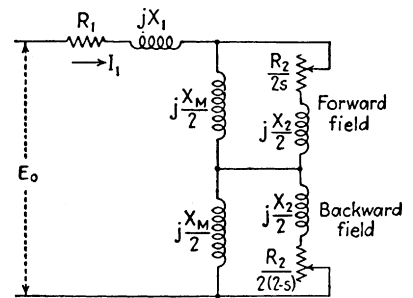


FIGURE 20-40 Equivalent circuit of single-phase induction motor.

Shaded-Pole Motor. The simplest way of providing a single-phase induction motor with starting torque is to place a permanently short-circuited winding of relatively high resistance in the stator at an electrical angle of 30° to 60° from the main winding. Usually this auxiliary winding, called a “shading coil,” consists of an uninsulated copper strip encircling approximately one-third of a pole pitch. The current induced in the shading coil, by the portion of the main field linking it, reduces the magnitude of this flux and also causes it to lag in time phase. In consequence, the air-gap field has two components, an undamped alternating flux and a damped flux displaced both in space and in time. Shaded-pole motors are used only in very small sizes normally below 50 W output. Principal applications are for desk fans and air circulators, where their simplicity, low torque, and low cost are well suited to the requirements.

The inherently high slip of a shaded-pole motor makes it convenient to obtain speed variation on a fan load by reducing the impressed voltage. It is common practice to provide multispeed fan operation by employing a small switched-series reactor or a phase-controlled solid-state device to control the motor voltage.

Resistance Split-Phase Motors. A considerably greater starting torque can be obtained by providing a separate starting winding, or auxiliary phase, 90° displaced in space from the main winding of a single-phase induction motor. This extra winding is normally wound with fewer turns of a much smaller size of wire, so that it has a considerably greater resistance to reactance ratio than the main winding, and it is connected directly across the power supply, in parallel with the main winding. Just as in the case of the shaded-pole motor, the field of the auxiliary winding is displaced in time and in space, so that its vectorial combination with the main field gives a much larger forward than backward field component. The motor can be reversed by reversing either the main or the auxiliary winding.

Since the auxiliary winding is normally located 90° from the main winding, the two are mutually noninductive at standstill and the standstill characteristics may be calculated from two independent circuits each like that of Fig. 20-40. By a similar analysis to that of the preceding section, the starting torque of a split-phase motor is

$$T = \frac{14.1aK}{N_s} I_M I_A R_2 \sin \theta \quad \text{ft} \cdot \text{lb} \quad (20-31)$$

where I_M = main winding starting current in amperes; I_A = auxiliary winding starting current in amperes; N_s = synchronous speed; R_2 = resistance component of standstill impedance of main winding, less the primary resistance; a = ratio of effective number of turns in auxiliary winding to main-winding effective turns; K = an empirical coefficient, which allows for nonfundamental rotor losses, usually equal to 0.9; and θ = angle of phase split between I_M and I_A .

Design limitations usually prevent θ from being greater than 30° , so that the starting torque per voltampere cannot exceed half that of a 2-phase motor built in the same parts. Since, in addition, both I_M and I_A are drawn from a single phase of the power supply, the starting current is excessive, limiting the use of the resistance split-phase motor to sizes below $1/3$ hp.

The auxiliary winding is opened automatically as the motor approaches full speed, as otherwise prohibitive losses would occur in it. Usually this is accomplished by means of a centrifugal switch or, in the case of hermetically sealed motors, by an electromagnetic relay. The high current density used to obtain an adequate resistance value makes the initial rate of temperature rise of the auxiliary winding very great, sometimes more than 50°C/s , so that these motors are not satisfactory for repeated starting or for inertia loads.

Earlier split-phase motor designs included motors with stationary external squirrel-cage members, with the primary windings on the rotor, receiving their power through slip rings. They are now normally built, however, with uniformly distributed partly closed stator slots, enameled-wire concentric stator windings, and a cast-aluminum or welded-copper squirrel cage on the rotor.

Typical characteristic curves for a $1/6$ -hp 60-Hz 1725-r/min, resistance split-phase motor are shown in Table 20-11.

Repulsion-Start Induction-Run Motor. A common way of obtaining single-phase-motor starting torque is to provide a dc winding and commutator on the rotor, with a single pair of short-circuited

brushes for starting and a centrifugal mechanism, which short-circuits the entire commutator as the motor approaches full speed. This gives a pure repulsion-motor starting characteristic with very high torque per ampere and pure single-phase induction-motor operating characteristics. These motors are widely used in sizes up to about 5 hp. Typical characteristics of a 1-hp 60-Hz 1800-r/min motor of this type are shown in Table 20-11.

Capacitor Motors. Low-cost low-voltage capacitors have proved extremely useful in improving the performance of split-phase motors. By inserting an external series capacitor in the auxiliary winding circuit and making this winding with many more turns of much lower resistance, the angle of phase split θ can be increased to 90° , or even more, and the coincident increase in the turn ratio a permits a further decrease in the auxiliary winding current. Thus, the capacitor-start motor gives an adequate starting torque for a reasonable starting current and at the same time has so much greater thermal capacity than a resistance split-phase motor, by virtue of the reduced winding-current density, that it is satisfactory for nearly all industrial single-phase motor applications.

Figure 20-41 illustrates a convenient method of determining the best size of capacitor to use with a given motor. I_M represents the locked-rotor current in the main winding and I_A the current in the auxiliary winding. With no external capacitor, $X_C = 0$, and the motor becomes a plain resistance split type. As X_C is increased, I_A moves ahead in time phase, following a circular locus, increasing the torque and reducing the total current drawn from the line. Points of maximum starting torque and maximum starting torque per ampere are indicated on the diagram.

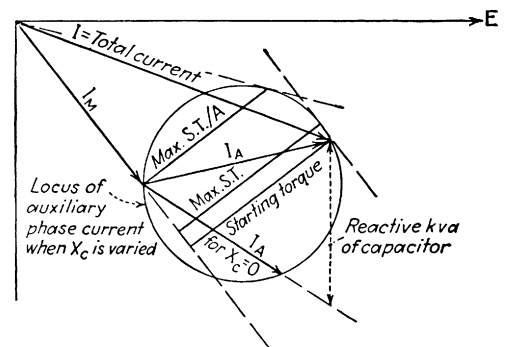


FIGURE 20-41 Capacitor-motor, starting-torque diagram.

Usually low-voltage electrolytic capacitors are used for starting purposes, since these are economical in 115-V intermittent ratings.

However, in cases of severe starting duty, higher-voltage motors, or where capacitors are retained in the circuit during operation, paper or film-type, oil-filled ac capacitors are used.

For most applications, the auxiliary winding is opened by a centrifugal switch or relay, as the motor approaches full speed, just as in the case of the resistance split-phase motor. Such motors are called *capacitor-start motors*. In some cases of smaller-sized motors with low-starting-torque requirements, however, it is permissible to leave the capacitor permanently in circuit. These are called *permanent-split capacitor motors*. The limitations of starting torque and motor size on this type are the result of the inherent tendency of the auxiliary-winding current to increase in magnitude and shift backward in time phase as the motor accelerates, so that unless the capacitor impedance is very high, the motor will have objectionable losses and large torque pulsations at full speed. However, the power loss in the capacitor circuit at speed is very much less than in a shading coil for a given starting torque, and so the permanent-split capacitor motor is finding increasing use for fan drive in sizes up to $1/4$ hp.

For the larger capacitor motors, in sizes of $1/2$ hp and up, it is frequently economical to retain the auxiliary winding in circuits with a reduced capacitor size, to improve the operating characteristics. This is usually accomplished by providing a large electrolytic or highly stressed capacitor in parallel with a small oil capacitor at starting and cutting the former out of circuits with a centrifugal switch or relay when the motor approaches full speed. Such motors are called *capacitor-run motors* and have winding connections as shown in Fig. 20-42. The analysis of the capacitor motor

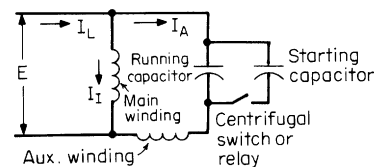


FIGURE 20-42 Capacitor-run, motor-winding connections.

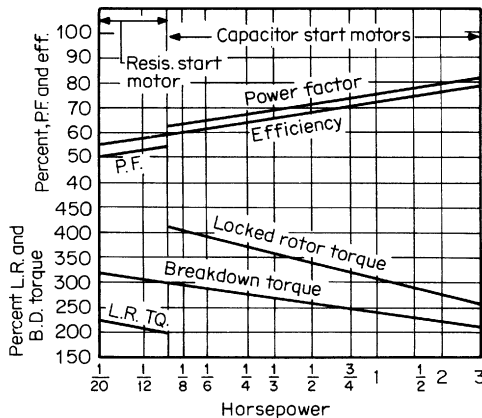


FIGURE 20-43 Typical operating characteristics of 1800-r/min single-phase motors.

TABLE 20-9 Standard Horsepower and Speed Ratings—Single-Phase Constant-Speed Motors

Standard horsepower ratings					
$\frac{1}{20}$	$\frac{1}{6}$	$\frac{1}{2}$	$1\frac{1}{2}$	5	15
$\frac{1}{12}$	$\frac{1}{4}$	$\frac{3}{4}$	2	$7\frac{1}{2}$	20
$\frac{1}{8}$	$\frac{1}{3}$	1	3	10	25
Standard speed ratings					
Rpm 60 cycles	Fractional hp		Integral hp		
3600	$\frac{1}{20}$ –1		$1\frac{1}{2}$ –25		
1800	$\frac{1}{20}$ – $\frac{3}{4}$		1–25		
1200	$\frac{1}{20}$ – $\frac{1}{2}$		$\frac{3}{4}$ –25		
900	$\frac{1}{20}$ – $\frac{1}{3}$		$\frac{1}{2}$ –25		
Rpm 50 cycles	Fractional hp		Integral hp		
3000	$\frac{1}{20}$ –1		$1\frac{1}{2}$ –20		
1500	$\frac{1}{20}$ – $\frac{3}{4}$		1–20		
1000	$\frac{1}{20}$ – $\frac{1}{2}$		$\frac{3}{4}$ –20		
750	—		$\frac{1}{2}$ –20		

Efficiencies and Power Factors. Typical efficiencies and power factors of the various types of induction motor that might be used to fill the requirements of the different ratings are shown in Fig. 20-43. Repulsion-start induction-run motors have about the same efficiencies and power factors except in the $1\frac{1}{2}$ -to 3-hp range, where they are lower. Repulsion-induction motors have roughly the same efficiencies but higher power factors.

Single-Phase Motor Characteristics. The full-load current of a single-phase motor is equal to

$$\frac{746 \times \text{hp}}{\text{Efficiency} \times \text{voltage}} \quad (20-32)$$

where the efficiency and power factor are expressed as decimals. Approximate values of full-load current are given in Table 20-10. These are used for selecting wire and fuse sizes if no more accurate data are available.

is done with an equivalent circuit of the type shown in Fig. 20-43 with the capacitors properly introduced.

Horsepower, Speed, and Voltage Ratings. Standard horsepower and speed ratings of single-phase motors are given in Table 20-9. Motors built in frames having a continuous rating of less than 1 hp, open type, at 1700 to 1800 r/min are designated *fractional-horsepower* motors, and those built in larger frames are called *integral-horsepower* motors. Somewhat different standards of performance have been established for the two classes. ANSI C-50 and *NEMA Motor and Generator Standards*, Publ. MG1-1978, include basic standards for both fractional- and integral-horsepower motors which are normally followed in specifications and testing.

Both capacitor and split-phase motors are available in the multispeed as well as the single-speed type. They are used principally for belt and direct drive of centrifugal and propeller fans and are of the variable-torque class. The multispeed motors for fan drive allow a change in fan speed without changing pulleys, which is essential where remote or automatic control of the rate of air delivery is required.

The standard voltage ratings for single-phase motors are 115 and 230 V for supply lines rated 120 and 240 V. Power companies place a limit on the size of motors that may be connected to single-phase lines. The limit usually falls between $\frac{1}{2}$ and 1 hp for 120-V circuits and between 3 and 10 hp for 240-V circuits.

Temperature Rise. The standard temperature rises and service factors for single-phase motors are the same as for polyphase motors.

TABLE 20-10 Single-Phase Motor Characteristics

Hp	Approximate full load, A		Locked rotor, A		Breakdown torque (for defining hp ratings), oz · ft above line; lb · ft below line				
	115 V	230 V	115 V	230 V	3600 rpm	1800 rpm	1200 rpm	900 rpm	
	1/6	4.4	2.2	10	8.7–11.5	16.5–21.5	24.1–31.5	31.5–40.5	
		5.8	2.9	11 1/2	11.5–16.5	21.5–31.5	31.5–44.0	40.5–58.0	
Fractional hp	1/4	7.2	3.6	15 1/2	16.5–21.5	31.5–40.5	44.0–58.0	58.0–77.0	
	1/3	9.8	4.9	22 1/2	21.5–31.5	40.5–58.0	58.0–82.5		
	1/2	13.8	6.9	30 1/2	31.5–44.0	58.0–82.5	5.16–6.9		
	3/4								
Integral hp	1	16	8						
	1 1/2	20	10						
	2	24	12						
	3	34	17						
	5	56	28						
	7 1/2	80	40						
	10	100	50						

Note: 1 oz · in = 0.00706 N · m; 1 lb · ft = 1.356 N · m.

Characteristics of a 60-Hz, 4-pole, 1800-r/min, single-phase motor are shown in Fig. 20-43.

The horsepower rating of a single-phase motor is defined by its breakdown torque. Thus, any 1800-r/min motor with a breakdown torque between 31.5 and 40.5 oz · ft is, by definition, a $\frac{1}{3}$ -hp motor. The value used for definition is the minimum of the range of manufacturing variation for that particular design.

Starting Current. Maximum values of locked-rotor current are established by NEMA for 60-Hz motors as shown in Table 20-10. In integral-horsepower sizes, NEMA has established two sets of locked-rotor values. The Design L motors include those types having inherently higher locked-rotor values. The Design M motors include those types having inherently higher locked-rotor current than Design L motors.

20.5 OTHER TYPES OF ELECTRIC MOTORS AND RELATED APPARATUS

Induction Generators. Any induction motor, if driven above its synchronous speed when connected to an ac power source, will deliver power to the external circuit. The generator operation is easily visualized from the equivalent circuit of Fig. 20-28, corresponding to negative slip. The induction generator must always take reactive power from the load or the line for excitation and for the PX losses. For this reason, the induction generator can only operate in parallel with an electric power system or independently with a load supplemented by capacitors. For independent operation, the speed must be increased with load to maintain constant frequency; the voltage is controlled with the capacitors.

An induction generator delivers an instantaneous 3-phase short-circuit current equal to the terminal voltage divided by its locked-rotor impedance. Its rate of decay is much faster than that of a synchronous generator of the same rating, corresponding to the subtransient time constant T'_{do} ; sustained short-circuit current is zero.

The virtue of the induction generator is its ability to self-synchronize when the stator circuit is closed to a power system. At one time induction generators were used for small, unattended hydro stations. Since the late 1990s, induction generators have been used in a similar manner for wind turbines and cogeneration units. They have also been used for high-speed, high-frequency generators, because of their squirrel-cage rotor construction.

Synchronous Induction Motors. There are three types of motors that can start and run as induction motors yet can lock into the supply frequency and run as synchronous motors as well. They are (1) the wound-rotor motor with dc exciter, (2) the permanent-magnet (PM) synchronous motor, and (3) the reluctance-synchronous motor. The latter two types have been used primarily with adjustable-frequency inverter power supplies. In Europe, wound-rotor induction motors have often been provided with low-voltage dc exciters that supply direct current to the rotor, making them operate as synchronous machines. With secondary rheostats for starting, such a motor gives the low starting current and high torque of the wound-rotor induction motor and an improved power factor under load. Several different forms of these synchronous induction motors have been proposed, but they have not shown any net advantage over usual salient-pole synchronous or induction machines and are very seldom used in the United States. The PM synchronous motor is shown in Fig. 20-44a. The construction is the same as that of an ordinary squirrel-cage motor (either single or polyphase), except that the depth of rotor core below the squirrel-cage bars is very shallow, just enough to carry the rotor flux under locked-rotor conditions. Inside this shallow rotor core is placed a permanent magnet, fully magnetized. The rotor core serves as a keeper, so that the rotor is not demagnetized by removing it from the stator. In starting, the rotor flux is confined to the laminated core. As the speed rises, the rotor frequency decreases and the rotor flux builds up, creating a pulsating torque with the field of the magnet, as when a synchronous motor is being synchronized after the dc field has been applied. As the motor approaches full speed, therefore, the ac impressed field locks into step with the field of the magnet and the machine runs as a synchronous motor. The absence of rotor I^2R loss,

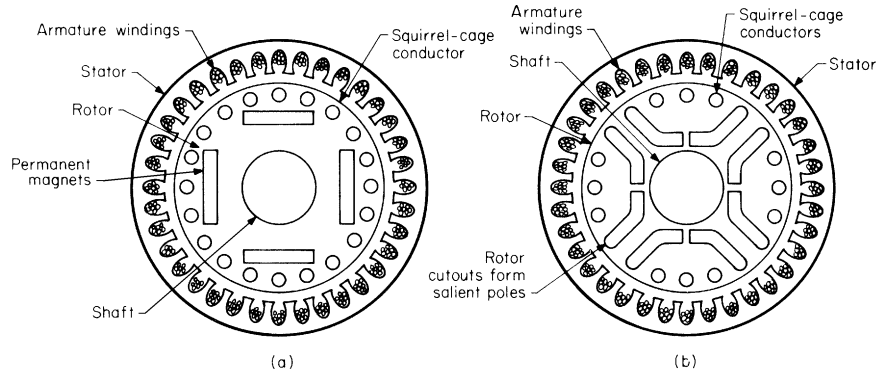


FIGURE 20-44 Cross section of (a) a conventional PM synchronous motor and (b) a reluctance-synchronous motor.

the synchronous speed operation, and the high efficiency and power factor make the motor very attractive for special applications, such as high-frequency spinning motors. When many such motors are supplied from a high-frequency source, the kVA requirements are reduced to perhaps 50% of those needed for usual induction motor types, with consequent large savings.

If the rotor surface of a P -pole squirrel-cage motor is cut away at symmetrically spaced points, forming P salient poles, the motor will accelerate to full speed as an induction motor and then lock into step and operate as a synchronous motor. The synchronizing torque is due to the change in reluctance and, therefore, in stored magnetic energy, when the air-gap flux moves from the low- into the high-reluctance region. Such motors are often used in small-horsepower sizes, when synchronous operation is required, but they have inherently low pull-out torque and low power factor, and also poor efficiency, and therefore require larger frames than the same horsepower induction motor. The PM synchronous motor has superior performance in every way, except possibly cost. A cross section of the reluctance-synchronous motor is shown in Fig. 20-44b. These motors are available up to about 5 hp.

If the number of rotor salients is nP , instead of P , and if the P -pole motor winding is arranged to also produce a field of $(n - 1)P$ or $(n + 1)P$ poles, the motor may lock into step at a subsynchronous speed and run as a subsynchronous motor. For the P -pole fundamental mmf, acting on the varying rotor permeance will create $(n + 1)P$ and $(n - 1)P$ -pole fields from this case, and these will lock into step with the independently produced $(n - 1)P$ - or $(n + 1)P$ -pole field, when the rotor speed is such as to make the two harmonic fields turn at the same speed in the same direction.

It is difficult to provide much torque in such subsynchronous motors, and their use is therefore limited to very small sizes, such as may be used in small timer or instrument motors.

Linear Motors. Linear induction motors (LIMs) have been built in fractional-horse-power ratings for such applications as moving drapes, and up to several thousand horsepower for driving tracked air-cushion transit vehicles on a guideway. Other applications include moving freight cars in yards, driving people-mover vehicles, and providing reciprocating motion for machine tools. LIMs are built like rotary induction motors with distributed multipole polyphase windings placed in the slots of a plane laminated stator as shown in Fig. 20-45. When the windings are excited by a polyphase voltage of frequency f , an air-gap space flux wave is propagated along the length of the stator at a velocity of $v = 2fp$, where p is the pole pitch. The rotor consists of an aluminum or copper sheet, which is propelled by the field with a slip velocity to provide the required thrust. LIMs are either double-sided, with two facing stators operating on a single rotor, or single-sided, with the rotor sheet backed by a moving or stationary magnetic return path. The magnetic force density normal to the stator surface is considerable compared to the tangential force density that moves the rotor, which requires that the stator be well braced mechanically to maintain constant air-gap distances over the surface of the stator. The typical tangential force density is about 3 lb/in² for air-cooled windings, where the normal force density is about 30 lb/in².

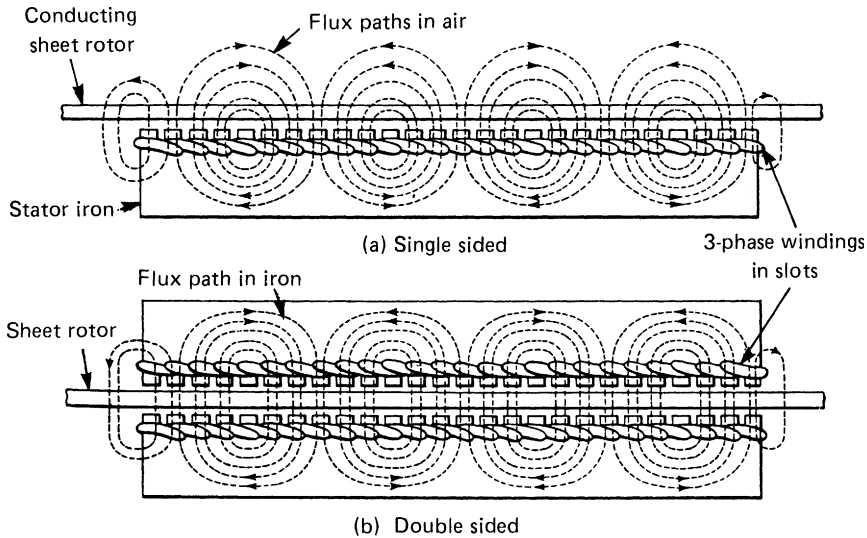


FIGURE 20-45 (a) Single-sided and (b) double-sided linear induction motors (LIMs) with sheet rotor.

The magnetic air gap of a double-sided LIM is the thickness of the sheet rotor plus the clearance between the rotor and the stators on either side. Whereas most rotary induction motors are built with an air gap of 0.025 to 0.1 mils, the air gap in the LIM is 0.25 to 1.5 in. For this reason, the magnetizing reactance of the LIM is lower than that of an equivalent rotary induction motor. Also the stator leakage reactance is higher. The equivalent circuit of the LIM is shown in Fig. 20-46a. Figure 20-46b shows the thrust-slip power factor and efficiency curves of a double-sided LIM. This LIM has an air gap of 1.47 in, a rotor sheet thickness of 0.25 in, and a stator length of 9.8 in. The two 3-phase windings of the stator are excited at 173 Hz from inverters to produce a linear synchronous velocity of 395 ft/s. Speed control and breaking of LIMs is done in the same way as in the rotary induction motors.

High-Frequency Motors. For high-speed tools and for spinning of rayon and other threads, a variety of interesting motor constructions have been developed. Normally these are 2-pole 3-phase motors, with special high-frequency power supply of 90, 120, or 180 Hz, giving operating speeds between 500 and 10,500 r/min and up to 25 hp. In textile applications, the motors usually drive individual spinning buckets, which are subject to considerable unbalance due to uneven building up of

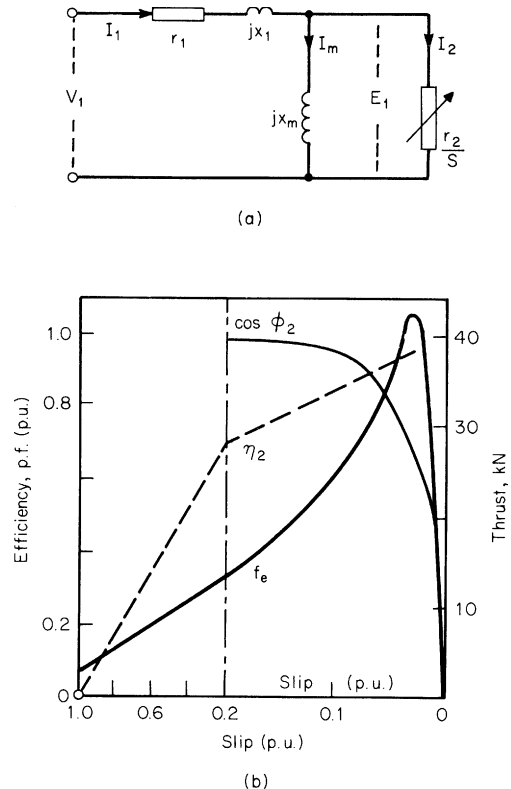


FIGURE 20-46 (a) Equivalent circuit of a double-sided LIM, (b) the characteristic curves of a typical LIM.

thread, etc. The continual starting and stopping for loading and unloading the buckets requires the motors to carry unbalance reliability through the entire speed range, necessitating careful design of mounting flexibility and shaft stiffness. Most usual applications, however, are in woodworking and similar industries, where separate motor stators and rotors are supplied to the tool manufacturers for building into their particular devices. These motors were powered from high-frequency alternators, but are now powered by adjustable-frequency solid-state inverters.

Three-phase 400-Hz power systems, used on large airplanes, have led to the development of 400-Hz motors with speeds of 12,000 and 24,000 r/min, having weights averaging 2 lb/hp for motors of 1 to 15 hp with 5-min ratings. These motors are open, with an external fan to force air over the windings.

Stepper Motors. The primary characteristic of a stepper motor is its ability to rotate a prescribed small angle (step) in response to each control pulse applied to its windings. Below about 200 pulses per second, the motor rotates in discrete steps in synchrony with the pulses; at higher frequencies up to 16,000 pulses per second, the motor skews without stopping between pulses. Although motors are available for step angles of 90° to 0.180° , the common step is 1.8° . Stepper motors are categorized as permanent-magnet rotor (PM), variable reluctance (VR), or hybrid (PM-VR). The rotor of the PM aligns itself with the energized stator poles as shown in Fig. 20-47b. The rotor turns until

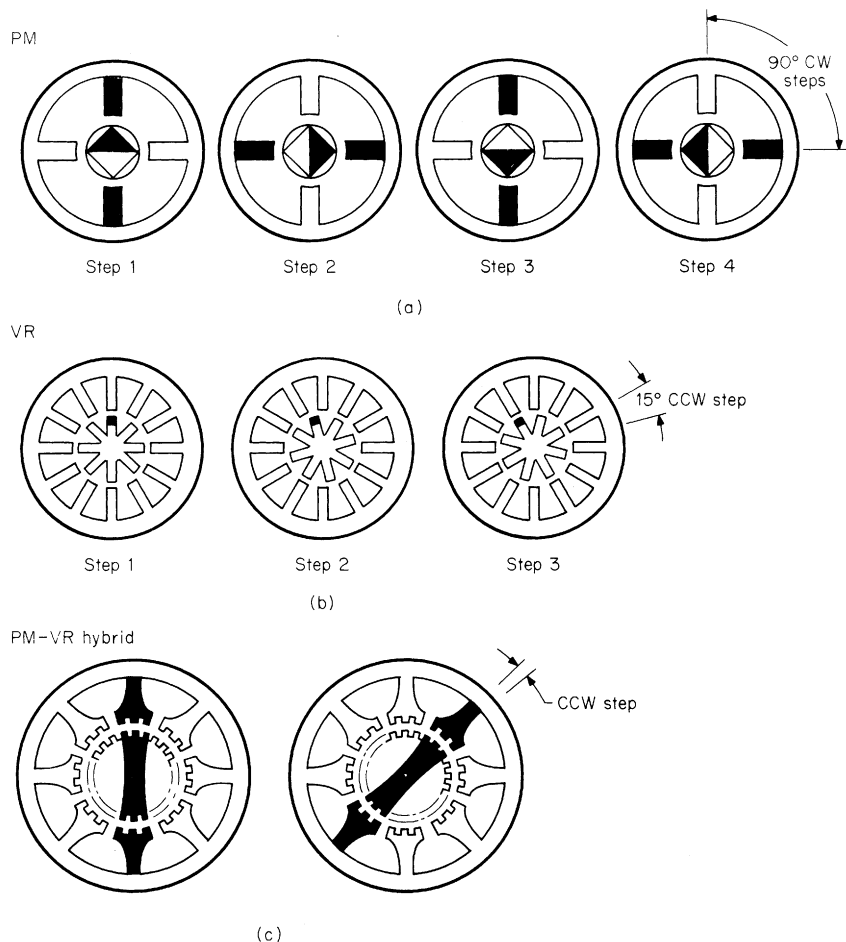


FIGURE 20-47 Three types of stepper motor.

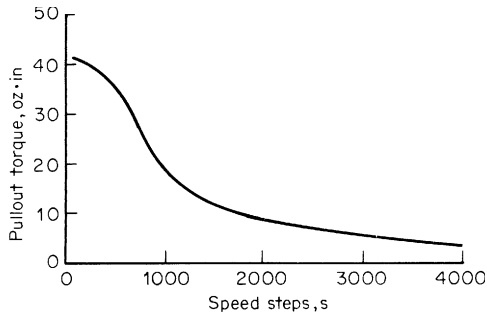


FIGURE 20-48 Pull-out torque vs. speed for a 4-phase 5° step VR step motor running at half steps ($2\frac{1}{2}^\circ$).

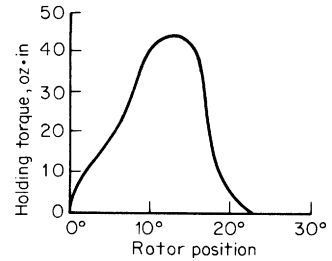


FIGURE 20-49 Holding torque vs. rotor position for a 3-phase, VR step motor, 24 steps per revolution, bidirectional, 1600 steps/s.

the poles are aligned at each step. The PM-VR hybrid shown in Fig. 20-47c has a high skew rate yet retains holding torque when the power is turned off. Motors can be made to rotate in half-steps to increase accuracy. Performance of stepper motors is described by two types of curves: the pull-out torque versus speed curve, as shown in Fig. 20-48; and the holding torque angle curves, as shown in Fig. 20-49. Stepper motors are available with holding torques up to 4000 oz·in.

Hysteresis Motors. By constructing the secondary core of an induction motor of hardened magnet steel, in place of the usual annealed low-loss silicon-steel laminations, the secondary hysteresis loss can be greatly magnified, producing effective synchronous motor action. Such hysteresis motors, having smooth rotor surfaces without secondary teeth or windings, give extremely uniform torque, are practically noiseless, and give substantially the same torque from standstill all the way up to synchronous speed. A hysteresis motor is a true synchronous motor, with its load torque produced by an angular shift between the axis of rotating primary mmf and the axis of secondary magnetization. When the load torque exceeds the maximum hysteresis torque, the secondary magnetization axis slips on the rotor, giving the same effect as a friction brake set for a fixed torque.

Despite the interesting characteristics of this type of motor, it is limited to small sizes, because of the inherently small torque derivable from hysteresis losses. Only moderate flux densities are practicable, owing to the excessive excitation losses required to produce high densities in hard magnet steel, and, therefore, about 20 W/lb of rotor magnet steel represents the maximum useful synchronous power on 60 Hz. Hysteresis motors have found an important use for phonograph-motor drives, their synchronous speed enabling a governor to be dispensed with and freedom from tone waver to be secured.

The Telechron motor, which is so widely used for operating electric clocks, also operates on the hysteresis-motor principle. In the Telechron motor, a 2-pole rotating field is produced in a cylindrical air space, and into this space is introduced a sealed thin-metal cylinder containing a shaft carrying one or more hardened magnet-steel disks, driving a gear train. The 60-Hz magnetic field causes the steel disks to revolve at 3600 r/min, driving through the gears a low-speed shaft, usually 1 r/min, which merges from the sealed cylinder through a closely fitting bushing designed to minimize oil leakage. Although the magnetic field has to cross a very considerable air-gap length and pass through the tin walls of the metal cylinder, the power required to drive a well-designed clock is so small that sample output is obtained with only about 2-W input for ordinary household-clock sizes.

The hysteresis motor has been displaced for phonograph and tape-reel drives by the transistor-driven brushless dc motor. It has been displaced for electric clocks by solid-state circuits with digital readout.

20.6 ALTERNATING-CURRENT COMMUTATOR MOTORS

Classification. As compared with the induction motor, the ac commutator motor possesses two of the advantages of the dc motor: a wide speed range without sacrifice of efficiency and superior starting

ability. In the induction motor, the starting torque is limited by the small space-phase displacement between the air-gap flux and the induced secondary current and by magnetic saturation of the flux paths. In the ac commutator motor, on the other hand, the air-gap flux and current are held at the optimum space-phase displacement by proper location of the brush axis, and the secondary current is not limited by magnetic saturation, giving high torque per ampere at starting. Furthermore, the series commutator motor may be operated far above the induction-motor synchronous speed, giving high power output per unit of weight.

Alternating-current commutator motors may be grouped into two classes:

1. Those motors in which the resultant mmf providing the flux increases with the load. When operated from a source of constant voltage, the speed of such motors decreases with increasing load. They are termed *series motors* from the similarity of their characteristics to those of series-wound dc motors. The speed at any given load may be varied by changing the applied voltage or, in some cases, by shifting the brushes.
2. Those motors in which the resultant mmf providing the flux is substantially constant irrespective of the load. For operation from a source of constant voltage, the speed of such motors is approximately constant. The speed may, however, be increased or decreased (independently of the load) by increasing or decreasing the voltage at the terminals of the motor, by brush shifting, or by the provision of suitably disposed and connected auxiliary coils. Such motors are termed *shunt motors*.

Alternating-current commutator motors are either single-phase or polyphase. A unique characteristic of all single-phase motors is a double line-frequency pulsation of the torque produced, corresponding to the sinusoidal variation twice each cycle of the single-phase power supplied. This torque pulsation is partly transmitted to the load, causing small speed pulsations and necessitating special coupling and mounting designs to minimize vibration and fatigue stresses.

Polyphase commutator motors have the advantage of better inherent commutating ability, due in part to the need for shifting the rotor current only 60° in time phase at each brush stud for a 6-phase motor or 30° for 12 phases, as compared with 180° shift for a single-phase or dc machine. Single-phase motors are generally limited to sizes below about 10 hp, except for railway applications.

With the advent of solid-state devices, the ac commutator motor is being displaced by the thyristor-rectifier-powered dc motors and inverter-fed induction motors, at less cost and superior performance. The dc motor does not have the difficulties of commutation, the requirement for extra windings, and shifting brush arrangements, and can be built on an unlaminated frame. The induction motor has no commutator and can run at the high speeds of the commutator motor.

Single-Phase Straight Series Motor. An ordinary dc series motor, if constructed with a well-laminated field circuit, will operate (although unsatisfactorily) if connected to a suitable source of single-phase alternating current. Since the armature is in series with the field, the periodic reversals of current in the armature will correspond with simultaneous reversals in the direction of the flux, and consequently the torque will always be in the same direction. But the inductance of the motor will be so great that the current will lag far behind the voltage, and the motor will have a very low power factor. The entire amount of armature flux produced along the brush axis generates a reactive voltage in the armature, which must be overcome by the applied voltage, without performing any useful function whatever.

When the motor is first thrown in the circuit, and before the armature has moved from rest, the field constitutes the primary of a transformer and sends flux through the armature core. Those armature turns, which at that instant are short-circuited under the brushes, act as short-circuited secondary coils and are traversed by heavy currents, which serve no useful purpose whatever and occasion serious heating. When the armature starts to revolve, these short-circuited turns are opened as they pass out from under the brushes and are replaced by other turns, which are momentarily short-circuited and then opened. These interruptions of heavy currents are accompanied by serious sparking, since the heating is concentrated at the few segments on which the brushes rest. As soon, however, as a certain speed is acquired, the heating is distributed over all the segments and the conditions are ameliorated. This source of sparking is, then, most serious at the moment of starting. This difficulty

has been minimized by operating at a lower frequency than 60 Hz and by the employment of leads of high resistance connecting the winding to the commutator segments.

The simple single-phase series motor has therefore two major faults, low power factor and poor commutation at low speeds, confining its use to fractional horsepower and very high speed applications.

Single-Phase Compensated Series Motor. In all except the smallest sizes, it is usual to employ a compensating winding on the stator, in series with the armature and so arranged that its mmf as nearly as possible counteracts the armature mmf. A commutating winding is also frequently used, which somewhat overcompensates the armature reaction along the interpolar, or commutating-zone, axis and so provides a voltage to aid the current reversal, just as in a dc motor. By these means, the flux along the brush axis is reduced to a small fraction of its uncompensated value, and the power factor of the motor is greatly improved. Further improvement of the power factor is secured by using a smaller air gap and correspondingly fewer field ampere-turns than in an uncompensated motor, thus reducing the reactive voltage in the series field to a minimum.

Universal Motors. Small series motors up to about $\frac{1}{2}$ -hp rating are commonly designed to operate on either direct current or alternating current and so are called *universal motors*. Universal motors may be either compensated or uncompensated; the latter type is used for the higher speeds and smaller ratings only. Owing to the reactance voltage drop, which is present on alternating current but absent on direct current, the motor speed is somewhat lower for the same load ac operation, especially at high loads. On alternating current, however, the increased saturation of the field magnetic circuit at the crest of the sine wave of current may materially reduce the flux below the dc value, and this tends to raise the ac speed. It is possible, therefore, to design small universal motors to have approximately the same speed-torque performance over the operating range, for all frequencies from 0 to 60 Hz. On a typical compensated-type $\frac{1}{4}$ -hp motor, rated at 3400 r/min, the 60-Hz speed may be within 2% of the dc speed at full-load torque but 15% or more lower at twice normal torque, while on an uncompensated motor the speed drop will be materially greater.

The commutation on alternating current is much poorer than on direct current, owing to the current induced in the short-circuited armature coils, and this provides a definite limitation on their size and usefulness. If wide brushes are used, the short-circuit currents are excessive and the motor-starting torque is reduced, while if narrow brushes are used, there may be excessive brush chatter at high speeds, causing short brush life. Good design, therefore, requires careful proportioning of commutator and brush rigging to meet conflicting electrical, mechanical, and thermal requirements. Universal motors are generally used for vacuum cleaners, portable tools, food mixers, and similar small devices operating at maximum speeds of 3000 to 10,000 r/min.

The speed of the universal motor is controlled by means of a half-wave thyristor, or full-wave triac, as shown in Fig. 20-50. The control device governs the half-wave average voltage applied

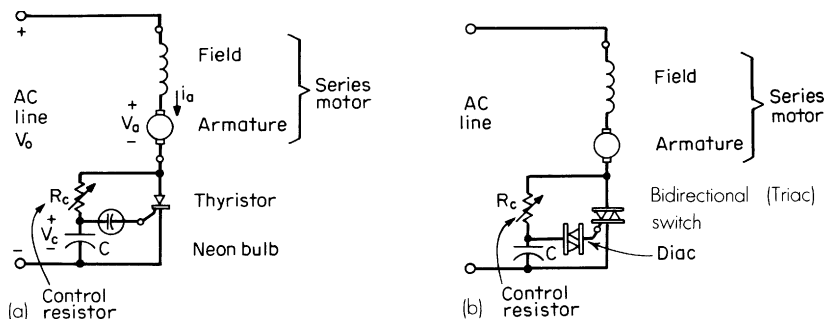


FIGURE 20-50 (a) Half-wave series universal motor circuit; (b) full-wave series universal motor circuit and the holding torque angle curves, as shown in Fig. 20-49. Stepper motors are available with holding torque up to 400 oz · in.

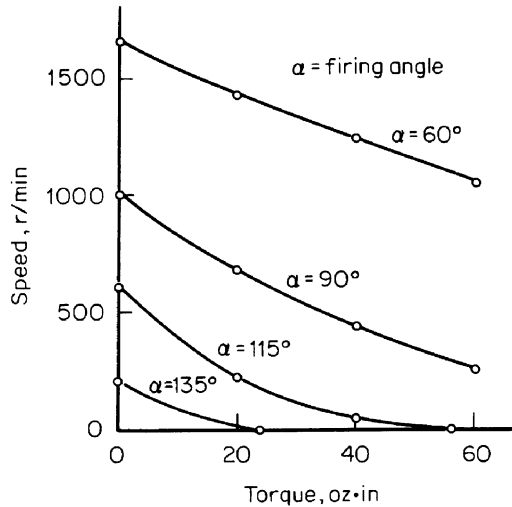


FIGURE 20-51 Measured speed-load torque characteristics of series motor and half-wave thyristor control.

to the motor as a function of the firing angle. The firing circuits are usually relatively simple. The speed is controlled by changing a resistance value, such as R_c , in Fig. 20-50. The characteristics of a universal (series) motor with half-wave control are shown in Fig. 20-51.

20.7 FRACTIONAL-HORSEPOWER-MOTOR APPLICATIONS

Scope. A fractional-horsepower motor is defined by NEMA as either (1) a motor built in a frame with a NEMA two-digit frame number or (2) a motor built in a frame smaller than the NEMA frame for a 1-hp, open-construction, 1700- to 1800-r/min, induction motor. The two-digit frame number is defined as 16D, where D is the height of the shaft centerline above the bottom of the mounting base. Fractional-horsepower motors include 1-phase and 3-phase induction and synchronous motors, 1-phase universal motors, and dc motors. Ratings, with minor exceptions, are $1/20$ to 1 hp, inclusive. Motors of smaller ratings are classified as subfractional or miniature.

Purpose. General-purpose motors are of open construction, rated at 60°C temperature rise by resistance over a 40°C ambient temperature. They are designed according to standard ratings with standard operating characteristics and mechanical construction for use under usual service conditions without restriction as to a particular application or type of application. A definite-purpose motor is any motor designed according to standard ratings with standard operating characteristics or mechanical construction for use under service conditions other than the usual or for on a particular type of application.

Selection of Type. The principal characteristics of fractional-horsepower motors are shown in Table 20-11. For any application, the motor selected should meet the application and power supply requirements at the least cost. Numerous trade-offs are possible, for example, speed changing infinite steps compared to continuously adjustable-speed solid-state drives.

Ratings. Standard voltage and frequency ratings are listed in Table 20-12a and 20-12b.

Service Conditions. General-purpose motors are designed to operate under the usual service conditions of 0 to 40°C ambient temperature, altitude to 3300 ft (1000 M), and installation on rigid mounting

TABLE 20-11 Characteristics of Fractional-Horsepower Motors

	Alternating current														
	Single-phase motors							1, 2, or 3 phase	Polyphase	DC or ac (60 Hz or less), universal types		Direct current			
	Split-phase types				Capacitor (1-value, or perm. split)	Repulsion-start	Shaded-pole			Nonexcited synchronous (reluctance)	Squirrel-cage induction	Without governor	With governor	Shunt or compound	Series
	General-purpose	High-torque	Two-speed, pole changing	Capacitor-start											
Schematic diagram of connections Arrangements shown are typical or representative; most of the types illustrated have numerous other arrangements which are also used.								Stator winding may be: split-phase, capacitor-start, capacitor, polyphase							
	Characteristic speed-torque curves Ordinates are speed: 1 division = for all ac motors, 20% of syn. r/min; for universal motors, 1000 r/min; for dc motors, 20% of full-load rpm. Each abscissa division = 100% of full-load torque.														
Rotor construction	Squirrel-cage	Squirrel-cage	Squirrel-cage	Squirrel-cage	Squirrel-cage	Drum-wound; commutator	Squirrel-cage	Cage, with cutouts	Squirrel-cage	Drum-wound; commutator	Drum-wound; commutator	None	Drum-wound; commutator		
Built-in automatic starting mechanism	Centrifugal switch	Centrifugal switch	Centrifugal switch	Centrifugal switch	None required	Short-circuit	None	Depends on stator winding	None	None	None	None	None		
Horsepower ratings commonly available	$1/20-1/5$	$1/6-1/5$	$1/8-3/4$	$1/8-3/4$	$1/20-3/4$	$1/8-3/4$	$1/2000-1/6$	$1/3000-1/5$	$1/6-3/4$	$1/50-1$	$1/30-3/4$	$1/25-1/30$	900—2000		
Usual rated full-load speeds (for 60-Hz ac motors; also dc motors)	3450, 1725, 1140, 865	1725	1725/1140, 1725/865	3450, 1725, 1140, 865	1620, 1080, 820	3450, 1725, 1140, 865	1450, —3000	3600, 1800, 1200, 900	3450, 1725, 1140, 805	3000—11,000	2000—4000	3450, 1725, 1140, 865	Varying, or adjustable varying		
Speed classification	Constant	Constant	Two-speed	Constant	Constant, or adjustable varying	Constant	Constant, or adjustable varying	Absolutely Constant	Constant	Varying, or adjustable varying	Adjustable	Constant, or adjustable varying	Resistor		
Means used for speed control			Two-speed switch		Two-speed switch or auto-transformer		Choke or resistor			Choke or resistor	Armature resistance				

Comparative torques Locked-rotor Breakdown Radio interference, running During acceleration	Moderate Moderate None One click	High High None One click	Moderate Moderate None Two click	Very high High None One click	Low Moderate None None	Very high High None Continuous	Low Low None None	Cutouts in synchronous- speed charac- teristics. Curve shown is for split-phase sta- tor. Pull-in ability is affected by inertia of con- nected load. Used for teleprinters, facsimile- picture trans- mitters, graphic instruments, etc. Clocks and timing devices usually use shaded-pole hysteresis motors rated at a few mil- lionths of a horsepower.	Companion motor to the capacitor- start motor with compa- rable torques and generally suited to make this type the universal char- acteristics of split-phase sta- tor. Pull-in ability is affected by inertia of con- nected load. Used for teleprinters, facsimile- picture trans- mitters, graphic instruments, etc. Clocks and timing devices usually use shaded-pole hysteresis motors rated at a few mil- lionths of a horsepower.	Light weight for a given output, high speeds, vary- ing-speed and universal char- acteristics of split-phase sta- tor. Pull-in ability is affected by inertia of con- nected load. Used for teleprinters, facsimile- picture trans- mitters, graphic instruments, etc. Clocks and timing devices usually use shaded-pole hysteresis motors rated at a few mil- lionths of a horsepower.	By means of a centrifugal governor, a constant- speed motor having the advantages of the universal motor for use where only de- power is avail- able. For unit- heater service, Governor may be sin- gle-speed or adjustable even while running. Speed is independent of applied voltage. Used in typewrit- ers, calculat- ing machines, food mixers, motion-pic- ture cameras and projec- tors, etc.	A constant- speed com- panion motor for the capaci- tor-start or split-phase motor for use where only de- power is avail- able. For unit- heater service, Governor may be sin- gle-speed or adjustable even while running. Speed is independent of applied voltage. Used in typewrit- ers, calculat- ing machines, food mixers, motion-pic- ture cameras and projec- tors, etc.	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	Very high Very high None None	Continuous Continuous	Continuous Continuous	
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TABLE 20-12 Voltage Ratings of (a) AC Fractional-Horsepower Motors and (b) DC Fractional-Horsepower Motors.

Motors	Frequency, Hz	Voltage
Single-phase	60	115, 230
	50	110, 220
3-Phase	60	115, 200
		230, (460)
	50	220, 380
Universal	60*	115, 230

*Can operate from dc to 60 Hz.

(a)

Primary power source	Rating, hp	Armature voltage	Field voltage
Los-ripple dc	$\frac{1}{20} - 1$	115, 230	115, 230
1-Phase rectifier	$\frac{1}{20} - \frac{1}{2}$	75	50, 100
		90	50, 100
		150	100
	$\frac{3}{4} - 1$	90	50, 100
		180	100, 200
3-Phase rectifier	$\frac{1}{4} - 1$	240	100, 150
			240

(b)

surfaces where there is no interference with the ventilation. Some general-purpose, definite-purpose, and special-purpose motors can operate under one or more unusual service conditions, which include exposure to dust, lint, fumes, radiation, steam, fungus, shock; operation where voltage, frequency, waveform, and form factor deviate from standards; and overspeed, overtemperature, and excess altitude operation. The manufacturer should be consulted for operation under unusual service conditions.

Thermal Protection. Many single-phase motors are now available with a built-in thermal protector, which affords complete protection from burnout due to any type of overload, even a stalled rotor. Most such devices are automatic-resetting, but some are manual-resetting. Motors that are protected usually are marked externally in some way to indicate the fact.

Reversibility. In general, standard motors of the types listed in the table can be arranged by the user to start from rest in either direction of rotation. There are exceptions, however. Shaded-pole motors, unless of a special design, can be operated in only one direction of rotation. Small dc and universal motors often have the brushes set off neutral, preventing satisfactory operation in the reverse direction. Single-phase motors, which use a starting switch ordinarily cannot be reversed while running at normal operating speeds, because the starting winding, which determines the direction of rotation, is then open-circuited. By use of special relays this limitation of split-phase and capacitor-start motors can be overcome when necessary. Such motors are built for small hoists. High-torque intermittent-duty permanent-split capacitor motors; repulsion-induction (buried-cage) motors; and split-series dc or universal motors are often built for plug-reversing service. Standard polyphase induction motors can be reversed while running, as can the smaller ratings of dc motors; such applications should preferably be taken up with the motor manufacturer.

Mechanical Features. Rigid and rubber-mounted motors are commonly available. Sleeve and ball bearings are both standard. Sleeve-bearing motors are designed for operation with the shaft horizontal, but ball-bearing motors can be operated with the shaft in any position. For operation with the shaft vertical, sleeve-bearing motors may require a special design. Rubber mounting is widely used for quiet operation, because all single-phase motors have an inherent double-frequency torque

TABLE 20-13 Approximate Starting and Full-Load Current for Single-Phase 115-V Motors

Rating, hp	Max. locked- rotor current, A		3450 r/min		1725 r/min		1140 r/min		865 r/min	
	Des. O	Des. N	A	W	A	W	A	W	A	W
$\frac{1}{8}$	50	20	2.9	207	2.7	176	3.9	207	5.4	245
$\frac{1}{6}$	50	20	3.2	254	3.0	214	4.3	254	6.0	296
$\frac{1}{4}$	50	26	4.2	352	3.9	301	5.6	352	8.1	414
$\frac{1}{3}$	50	31	5.3	460	4.9	395	7.0	460	9.8	540
$\frac{1}{2}$	50	45	7.4	678	6.9	574	9.8	678		
$\frac{3}{4}$	...	61	10.6	981	9.9	835				
1	...	80	13.3	1260						

Note: A = amperes; W = watts; Des. = Designation.

pulsation. An effective and common arrangement uses rubber rings concentric with the shaft and so arranged as to provide appreciable freedom of torsional movement but little other freedom. Sometimes the driven member picks up the double-frequency torque pulsation and amplifies it to an objectionable noise, for example, a fan with large blades mounted rigidly on the shaft. The cure for this difficulty is an elastic coupling between the shaft and the driven member; no amount of elastic suspension of the stator can help. Standard motors are generally open and of drip-proof construction. Splashproof and totally enclosed motors are easily available.

Inputs of Small Single-Phase Motors. See Table 20-13. Full-load torque, in terms of horsepower and rated speed, is

$$\text{Full-load torque, oz} \cdot \text{ft} = \frac{84,000 \times \text{hp}}{\text{r/min}} \quad (20-33)$$

Application Tests. The primary object of any application test is to determine the power requirements of the appliance or device under various significant operating conditions. A convenient way of doing this is to use a motor of approximately the right horsepower rating and of predetermined efficiency at various outputs. Watts input are carefully measured under each condition. From the watts input observed (never use current as a measure of load except for dc motors) and the known efficiency, the load is readily determined. Care should be taken in measuring the watts input to correct for the meter losses.

A second, and equally important, object of the test is to determine the actual locked-rotor and pull-up torques required by the appliance. The locked-rotor and pull-up torques of the test motor should be known or measured at rated voltage and frequency. (Locked-rotor torque often varies with slight changes in rotor position.) Using a transformer or induction regulator to obtain a variable voltage (do not use a resistance or choke for this purpose), measure the minimum voltage at which the motor will start the appliance and also the minimum voltage at which it will pull it up through switch-operating speed. Assuming that the pull-up and locked-rotor torques each vary as the square of the applied voltage, it is then a simple matter to determine the actual locked-rotor and pull-up torques required by the device. After a motor has been selected, it should be determined whether it can operate the device at 10% above and below normal rated voltage of the motor or over a wider range of voltage, if desired. If exceptional load conditions may occasionally be encountered, use of a motor equipped with inherent-overheating protection is often desirable.

Definite-Purpose Motors. For a number of important applications, involving large quantities of motors, NEMA has developed standards to meet these special requirements effectively and economically. Motors built to these standards are usually more readily obtainable and economical than special motors tailored to one application. Highlights and distinguishing features are given in Table 20-14. More details can be obtained in NEMA Standards.

TABLE 20-14 NEMA Standards for Definite-Purpose Motors

Application	Principal types	Distinguishing features
Universal motors	Universal: salient-pole and distributed field	Dimensional standards; common practices utilizing parts
Hermetic motors	Split-phase, capacitor-start, polyphase	Parts only for hermetic refrigeration condensing units
Belt-drive refrigeration compressors	Capacitor-start, repulsion-start, polyphase	Open; sleeve bearings, extended rear oiler; automatic-reset thermal overload protection
Jet-pump motors	Split-phase, capacitor-start, repulsion-start, polyphase	3450 r/min; ball bearings; open; machined back-end shield; automatic-reset overload protection
Motors for shaft-mounted fans and blowers	Split-phase, permanent-split capacitor, polyphase	Enclosed; horizontal; sleeve bearings; vertical, ball bearings; extended through bolts; capacitors on front end shield
Shaded-pole motors for shaft-mounted fans and blowers	Shaded-pole; two-speed, three speed	Open or totally enclosed; sleeve bearings; high slips
Belted fans and blowers	Split-phase, capacitor-start, repulsion-start; two-speed split-phase and capacitor-start	Open; sleeve bearings; resilient mounting; automatic-reset overload protection; extended rear oiler
Stoker motors	Capacitor-start; repulsion-start; polyphase	Totally enclosed recommended; automatic-reset overload protection
Motors for cellar drainers and sump pumps	Split-phase	Vertical, drip-proof, 50°C; two ball bearings, or one ball, one sleeve; mounts on support pipe; built-in float-operated line switch; overload protection
Gasoline-dispensing pumps	Capacitor-start, repulsion-start, polyphase	Explosionproof; sleeve bearing; built-in line switch and capacitor; voltage-selector switch on single-phase
Oil-burner motors	Split-phase	Enclosed, face-mounted, round-frame; manual-reset overload protection; two line leads
Motors for home-laundry equipment	Split-phase	Low-cost, high starting current; open, 50°C; round-frame with ungrounded mounting rings; shaft extension with flat and hole for coupling
Motors for coolant pumps	Split-phase, capacitor-start, repulsion-start, polyphase	3450- and 1725-r/min; totally enclosed; ball bearings; machined back-end shield
Submersible motors for deep-well pumps	Split-phase, capacitor, polyphase	3450 r/min; designed for operation totally submerged in water not over 25°C (77°F); use external relay for starting

Small Synchronous Motors. Small synchronous motors in the 1.5- to 25-W range for timing, tape drives, small fans, and record players are available as brushless dc motors or as hysteresis motors. The brushless dc motor consists of a permanent-magnet field, 2-phase, synchronous motor driven by transistors from a dc source. The transistors are switched from a Hall-device signal that senses the rotor position. A regulator maintains constant speed.

Shaded-pole hysteresis motors, which operate at synchronous speed, are essentially the same as shaded-pole induction motors except that they use rotors of hardened-steel rings of a material having high hysteresis loss. Large quantities of such motors are built for clocks and timing devices. Clock motors have an input of 1.5 to 2 W and an output of a few millionths of a horsepower. Large motors with inputs up to 15 W are built for heavier duty applications. Rotor speeds are commonly 450, 600, and 3600 r/min. Most of these motors are furnished with built-in reduction gears to give output speeds of 60 r/min to 1 r/month.

Reluctance motors, both self-starting and manual-starting types, are available for similar applications. Another type used is the synchronous-inductor motor, which is essentially an inductor alternator used as a motor; field excitation is furnished by a permanent magnet.

20.8 MOTOR CONTROL

Industrial motor control includes (1) motor-starting devices, (2) speed-control devices, (3) stopping devices, and (4) motor-protecting devices.

Industrial motor control is designed and built in accordance with rules and standards established by several organizations. Detailed design-construction and test information is contained in such publications as the *National Electrical Code*, National Board of Fire Underwriters; *Standards for Industrial Control Apparatus*, Institute of Electrical and Electronics Engineers; *Industrial Control Standards*, National Electrical Manufacturers Association; *Standard for Industrial Control Equipment*, Underwriters' Laboratories; and *Standard Rotation, Connections and Terminal Markings for Electric Power Apparatus*, American National Standards Institute.

The essential functions of motor control are the starting, speed regulating, stopping, and protecting of electric motors.

20.9 MOTOR-STARTING DEVICES

A *contactor* is a device, generally magnetically actuated, for repeatedly establishing and interrupting an electric power circuit.

Figure 20-52 illustrates a single-pole dc contactor. Contactors of this type are rated on a continuous-current-carrying-capacity basis and on an intermittent-duty basis, at values depending on the duty cycle. The NEMA Standard 8-h open ratings range from 25 to 2500 A. The intermittent ratings are $133\frac{1}{3}\%$ of the open ratings. The shunt-operating coil is designed to withstand 110% of rated voltage continuously and to close the contactor successfully at 80% of rated voltage.

The *magnetic blowout* consists of a coil wound on a steel core and mounted between steel pole pieces. The pole pieces are lined with refractory material. The assembly is enclosed in an insulated box, which is swung down over the contacts. The blowout coil is generally connected in series with the contactor and carries motor current with the contactor closed. The current sets up a magnetic field through the core and pole pieces of the blowout structure and across the contact tips. When an arc is formed, the magnetic field of the arc and the magnetic field of the blowout repel each other and the arc is forced upward and away from the contacts. The extinguishing action, due to the lengthening of the arc and the cooling of the refractory material, is extremely rapid and thereby greatly reduces the wear and burning of the contacts.

Several factors are important in the performance of contactors. To obtain trouble-free service and maximum contact life, the following items should be in accordance with the manufacturer's specifications: initial and final contact pressures, magnetic gap, arc gap, and wear allowance. The contact pressures can be measured by means of a spring balance, initial pressure with the contactor open,

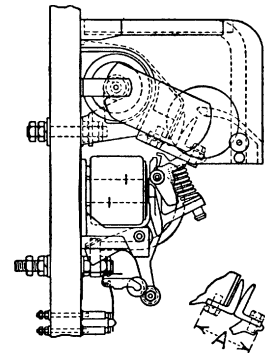
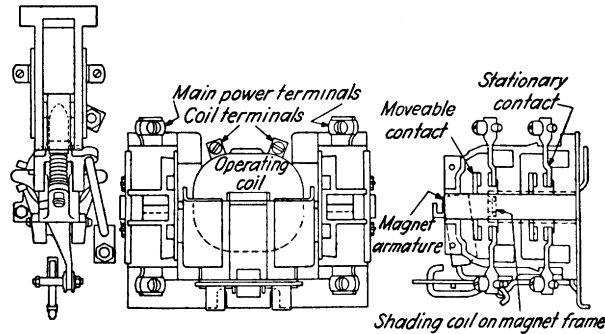


FIGURE 20-52 Direct-current contactor.

**FIGURE 20-53** Alternating-current contactor.

and final pressure with the contactor closed. The magnetic gap is the distance from the centerline of the core to a corresponding point on the armature lever, and the arc gap is the distance between the arcing tips. Contacts can be kept smooth by filing with a fine file. Contact-wear allowance is the total thickness of material that may be worn away before the contact between the two surfaces becomes ineffective. The contacts should be renewed when worn so that the distance A (Fig. 20-52) between the back edges of the contacts, with the contactor closed, becomes less than the specified amount. This usually corresponds to the condition where the contacts are worn to approximately half their original thickness.

Current-carrying contacts are usually made from copper, either left plain or plated with silver or cadmium. The contacts should not be lubricated. Hinge pins and bearings should be lubricated with a light machine oil. The surface of the core and the armature, which seal when the contactor is closed, should be kept clean.

An ac contactor is similar in construction to a dc contactor, except that laminated iron structures are used. A shading coil is used at the core face to ensure continuous force of the armature and thus obtain quiet operation. AC contactors are available with 2, 3, or 4 main poles for interrupting all line circuits to single-phase, 3-phase, or 2-phase 4-wire motors (see Fig. 20-53 and Table 20-15). Standard ac contactors are designed to interrupt 10 times rated motor current, based on the contactor horsepower rating. The contactors are also designed to thermally withstand 15 times rated motor

TABLE 20-15 Typical Ratings of AC Contactors Used as Across-the-Line Magnetic Starters with 3-Phase Motors

Contactor size	Rating, A	Horsepower at		
		110 V	220 V	440–550 V
00	9	$\frac{3}{4}$	$1\frac{1}{2}$	2
0	18	2	3	5
1	27	3	$7\frac{1}{2}$	10
2	45		15	25
3	90		30	50
4	135		50	100
5	270		100	200
6	540		200	400
7	810		300	600
8	1215		450	900
9	2250		800	1600

current for 1 s, to permit protective devices such as circuit breakers and fuses to clear fault current carried by the contactor.

A *drum switch* consists of stationary contact fingers held by spring pressure against contact segments on the periphery of a rotating cylinder or sector. Drum controllers have many advantages over the faceplate and multiple-switch types. The mechanical construction is better, heavy contact pressures can be maintained, parts can be well insulated, blowout magnets and arc shields can be used, and the structure can easily be completely enclosed. Less space is required by the drum control, and it is easier to operate. Drum controllers are built in 8-h ratings for dc motors up to 40 hp, 115 V, and 75 hp, 230 V.

The design of starting-duty resistors requires the determination of the total ohms, the distribution of this resistance between the steps available, and the calculation of the current-carrying capacity, and the selection of the resistance material. Standard resistors to meet various classes of service are designated by class numbers in accordance with the NEMA *Table of Classification of Resistors*. NEMA also publishes a resistor application table intended as a guide in specifying and designing resistors (see *NEMA Industrial Control Standards*). This table lists typical machines with the corresponding NEMA resistor-classification number. For example, a lathe should have a dc starter with resistor classification No. 115. This resistor has sufficient total ohms to limit the current inrush on starting to 150% of full-load current. It will be designed to have current-carrying capacity for an average accelerating current (rms value) of 125% full-load current, on the basis of starting once during each 80-s period and with an accelerating time of 5 s.

Resistors must be available in a wide range of ohmic values and current capacity. Resistor units are stacked in parallel and series combinations to achieve the required values. For low ohms and high capacity, cast-iron or punched-steel grids are used. These steel grids range from 0.01- Ω , 160-A to 0.40- Ω , 20-A continuous rating per grid. For high ohms and low capacity, wire-wound resistors are used with a unit resistance range from 4.0 to 6400 Ω and dissipation up to 900 W. Intermediate resistance requirements are fulfilled with edge-wound ribbon resistors with a unit resistance range of 0.05 to 8.6 Ω and dissipation up to 1320 W.

Resistors must be sized and arranged in assemblies so that the temperature rise for bare resistive elements does not exceed 375°C above 40°C ambient. The maximum current should not exceed the 10-s rating. Care must be taken to limit excess voltage on wire-wound resistors to avoid surface flashover. Resistors are generally insulated for 600 V rms to ground. Manufacturers will provide assembled resistor units for specific functions or provide the derating curves for the arrangement of the resistor units into assemblies, as a function of duty cycle, ambient temperature, and grouping.

20.9.1 AC Motor Starting

Selection of an ac starter is a compromise between requirements and cost. The primary requirements of the starter, obviously, are that the motor starting torque shall be adequate to start the load under worst-case line voltage and load conditions; also, that the line current shall not exceed limits set by the utility or plant voltage dip. A useful table is shown in Table 20-16. The available starters are listed in descending value of starting torque, based on a 60-hp, 440-V, 60-Hz, 900-r/min motor. Compared to the starters with series-connected elements, the autotransformer starter provides a means for reducing the line current below the motor current. The current and torque in Table 20-16 are shown for 100% line voltage. For reduced line voltage, the current is reduced in proportion; the torque is reduced as the square of the voltage. Limit on voltage dip is 15% to 20%.

The secondary requirements in starter selection include smoothness of acceleration, maintenance, power factor, reliability, and efficiency. The selection of a closed-transition starter depends upon whether the motor and the supply line can withstand the peak current as the time the starter transfers the motor to full voltage.

Alternating-current across-the-line starters are simple in construction, easy to install and maintain, and inexpensive. A typical starter consists of a 3-pole contactor with a thermal overload relay for protecting the motor. The starter connects the motor directly to the line, impressing full voltage to the motor terminals. It is particularly suitable for squirrel-cage motors. Since these starters connect the motor directly to the supply lines, the motor will draw an inrush current of 6 to 10 times running current. In the

TABLE 20-16 Comparison of Methods for Starting 3-Phase Motors
(Example of 60-hp, 900-r/min, 60-Hz motor)

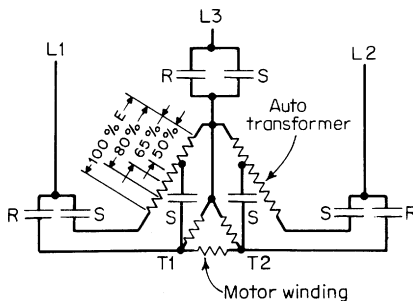
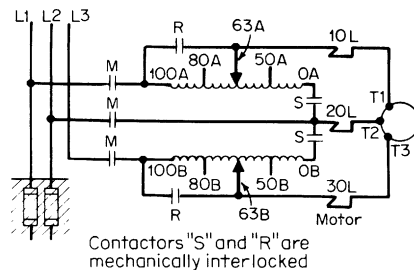
Method of starting	Starting current drawn from the line as a percentage of full-load current	Starting torque as a percentage of full-load torque
Connecting motor directly to the line full potential	470	160
Autotransformer 80% tap	335	105
Resistor starter to give 80% applied voltage	375	105
Part winding	235	70
Autotransformer 65% tap	225	67
Resistor starter to give 65% applied voltage	305	67
Solid-state starter	300	65
Star-delta starter	158	54
Resistance starter to give 58% applied voltage	273	54
Autotransformer 50% tap	140	43
Resistor starter to give 50% applied voltage	233	43

majority of installations this is not objectionable and will not damage the motor or the driven machinery. When the starting inrush must be lower, some form of reduced-voltage starting must be used. The common types of starters are autotransformer, primary-resistance, part winding, Y- Δ , and solid-state.

Autotransformer starters have two autotransformers connected in open Δ to provide reduced-voltage starting. Three taps are supplied, as shown in Fig. 20-54, giving 50%, 65%, and 80% of full line voltage. The motor current varies directly as the voltage impressed on the motor terminals. The line current varies as the square of the impressed voltage and is therefore lower than with resistor-type starters. The torque also varies as the square of the impressed voltage. The 50% voltage tap will therefore provide 25% starting torque. Connections should be made to the lowest tap that will give the required starting torque.

Characteristics of this type of starter are low line current, low power from the line, and a low power factor. Acceleration is not continuous, because the torque developed by the motor remains practically constant during the starting period, on the first step; then changes to another value on the second step. The starter shown in Fig. 20-54 is an open-transition type. The motor is disconnected from the line during the transfer period. A closed-transition starter which uses the Komdorfer connection is shown in Fig. 20-55. When the S contactor opens, the autotransformers act as series reactors until the R contactor closes.

Autotransformer starters are available in manual and automatic types. In the manual type the contacts are operated by means of a lever extending to one side of the enclosing case. The lever is equipped with a low-voltage release magnet. The automatic open-transition starter (Fig. 20-54) consists of a 5-pole starting contactor S and a 3-pole running contactor R . The closed-transition starter (Fig. 20-55) consists of a 3-pole main contactor (M) and 2-pole start and run contactors (S and R).

**FIGURE 20-54** Connections for autotransformer starter.**FIGURE 20-55** Connections for a closed-transition autotransformer motor starter.

When the “run” button is pressed, the starting contactor closes, connecting the transformer to the line and the motor to the reduced-voltage taps. A timing relay is operated by the starting contactor. The motor accelerates, and, after a specified number of seconds, the timer contacts close, deenergizing the starting contactor and energizing the running contactor. The transformer is disconnected and the motor connected to line voltage.

Primary-resistor-type starters connect the motor to the line through a series resistor. Reduced voltage at the motor is obtained because of the voltage drop across the resistor. As the motor accelerates, the current drawn from the line declines, and consequently the voltage drop across the resistor is lowered, and the motor voltage at the motor terminals is increased. The torque delivered by the motor is therefore constantly increased as the motor speed increases. After a definite interval, a timing device operated by the main contactor energizes the accelerating contactor, which short-circuits the resistor. There is no transfer period during which the motor may lose speed, and therefore smooth acceleration is obtained. In comparison with the autotransformer-type starter, the primary-resistor type takes more power from the line on starting but provides smoother acceleration, faster acceleration with a given initial torque, and higher power factor. In the smaller sizes, the primary-resistor starter costs less than the autotransformer starter.

In *part-winding ac starters*, the motor winding must be in two parts, and at least six terminal leads must be provided on the motor. The method is therefore applicable to those motors which are designed for use on either of two voltages, the windings being in parallel on the lower voltage and in series on the higher voltage. For example, a 230/460-V motor could be used on 230 V with a part-winding controller. The controller would then be arranged to connect one section of the winding to the supply lines as soon as the starting button is pressed. Then, after a time delay provided by a timing relay, a second contactor would connect the other section of the motor winding to the supply lines, in parallel with the first section. In this way, the starting current is reduced to approximately one-half of what would be required if both winding sections were connected at the same time, as they would be with a standard 3-lead motor. The starting torque when the first winding section is connected will be less than half of the torque that would be obtained if both sections were connected at the same time. Contactors used for part-winding starters need capacity to handle only the circuit which they control, and so may be rated at one-half of the rating that would be required to handle the whole motor. Overload relays are provided for each section of the winding.

Y-Δ ac starters are a form of reduced voltage starter used with 6-lead motors in which 57% voltage is applied to the windings on the first step, full voltage on the second step. The starting current and starting torque are 33% of the full-voltage values. The Y-Δ starter is used for compressors and other loads that can be unloaded for starting, or can tolerate the 33% starting torque.

Y-Δ starters are built for open-transition, as shown in Fig. 20-56, or closed-transition operation, as shown in Fig. 20-57. The open-transition starter operates as follows: Relay contactor *S* is energized, connecting the motor windings in Y. A normally open auxiliary contact on contactor *S* closes,

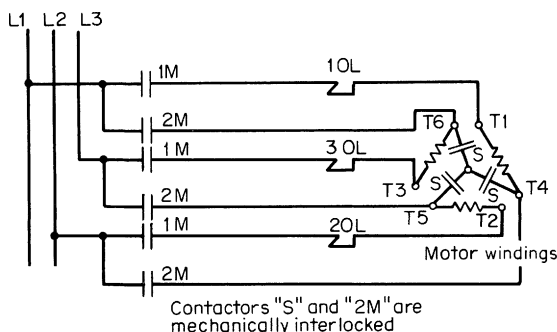


FIGURE 20-56 Open-transition Y-Δ starter.

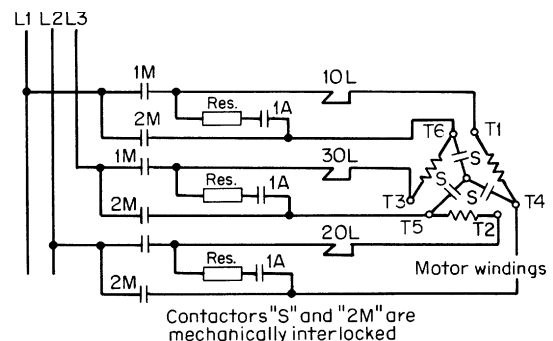


FIGURE 20-57 Closed-transition Y-Δ starter.

energizing contactor $1M$. Its contacts close, energizing the motor windings in Y. After a predetermined interval, the contactor is deenergized, contacts on timer TR open deenergizing contactor S , opening its contacts and thereby opening the Y-connected winding. The motor is now temporarily deenergized. A normally closed auxiliary contact on contactor S closes, energizing contactor $2M$ in addition to $1M$. The motor is reenergized in Δ .

The closed-transition starter of Fig. 20-57 operates as follows: Contactor S is energized, connecting the motor windings in Y. A normally open auxiliary contact on contactor S closes, energizing contact $1M$, closing its contacts, energizing the motor windings in Y. After a predetermined interval, contactor $1A$ is energized, connecting resistors Res in Y and paralleling them across the Y-connected motor winding. A normally closed auxiliary contact on contactor $1A$ opens, deenergizing contactor S , opening its contacts and placing resistors Res in series with the motor winding. The motor is now connected in Δ . A normally closed auxiliary contact on contactor S closes, energizing contactor $2M$, closing its contacts and thereby shorting out the resistors Res . The Δ -connected compressor motor is now energized at full voltage.

Solid-state ac starters employ back-to-back phase-controlled thyristors in two or three of the lines to the motor as shown in Fig. 20-58. The thyristors are controlled during the starting period to maintain about 300% line and motor current by gradually increasing the motor voltage from the initial value. Starting is smooth; the current and starting torque can be adjusted easily. The solid-state starter is applied where the line current is critical and where repetitive motor starting limits the life of electromagnetic contactors.

Slip-ring ac motor starters consist of a contactor to connect the motor primary to the supply lines and a resistor and resistor switching means for the secondary circuit. The starting torque depends on the ohmic value of resistance used; maximum torque is obtained when the resistance is selected for an inrush of approximately 3 times full-load current. Sufficient resistance is generally used to limit the inrush current to 150% or 200%. The resistor is cut out step by step as the motor accelerates, until the slip rings are short-circuited. The commutating means may be a faceplate controller, a drum, or a series of magnetic contactors controlled by current or time relays. High starting torque and low running slip can be obtained with a slip-ring motor.

20.9.2 DC Motor Starting

Direct-current motors of small capacity may be started by connecting the motor directly to line voltage. Motors rated 2 hp or more generally require a reduced-voltage starter. The reduced voltage for starting is obtained by using resistance in series with the motor armature or by varying the armature supply voltage. Manual or magnetic control may be used.

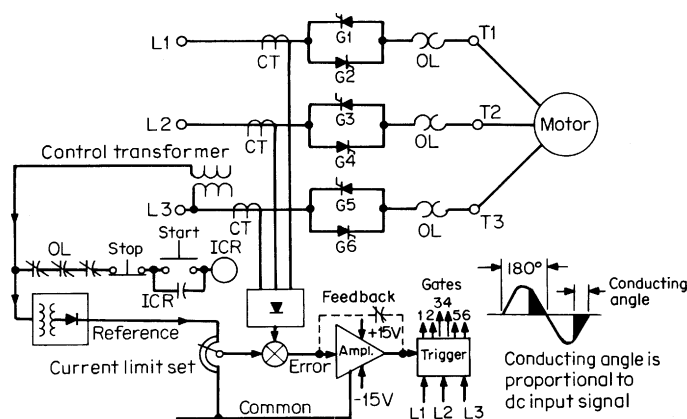


FIGURE 20-58 Diagram of solid-state ac motor starter.

DC motors in adjustable-voltage, adjustable-speed drives are started by turning the speed control up from zero to the desired speed, or by internal circuits that ramp the armature voltage to the desired value. Starting equipment, other than the armature-voltage rectifier or generator, is not required.

Direct-current manual starters are satisfactory for applications that do not require frequent starting and stopping and where the starter can be mounted near the operator without requiring long motor leads. Across-the-line starters provide the simplest means of starting small dc motors. Manually operated switches for this service are available in sizes up to 1.5 hp at 115 V and 2 hp at 230 V. For larger motors resistance is connected in series with the motor armature to limit the current inrush on starting. A manually operated means is then provided for removing the resistor from the circuit in a series of steps. Starters are available in the faceplate type, the multiple-switch type, and the drum type. The faceplate type is built for motors up to 35 hp, 115 V, and 50 hp, 230 V. It consists of a movable lever and a series of stationary contact segments to which sections of resistor are connected. The resistor sections are short-circuited one at a time by moving the lever across the segments.

Manual starters have generally been replaced by push-button-operated magnetic control that incorporates overload protection and other safety features.

Direct-current magnetic starters are used for applications where ease and convenience of operation are important; where the starter is operated frequently; where the motor is located at a distance from the operator; where automatic control by means of a pressure switch, limit switch, or similar device is desired; and for large motors which require the switching of heavy currents. Resistance is connected in series with the motor armature to limit the initial current and is then short-circuited in one or more steps.

For larger motors a series of magnetic contactors is used, each of which cuts out a step of armature resistance. The magnetic contactors are operated as the motor starts by one of two methods called *current-line acceleration* and *time-limit acceleration*; the starting time is always matched to the burden of the load. Time-limit acceleration is advantageous where the starting time of the motor must be integrated into a timing sequence for an overall machine or process. Examples of each will be given.

Figure 20-59 shows a type of *time-limit acceleration* where the operation of contactors, and therefore the rate of acceleration, is governed by a *magnetically operated definite time relay*. This time relay operates on the principle of discharging a capacitor, thus obtaining a definite time period, which is unaffected by changes in temperature and load or by dust and dirt. With the motor at rest, a circuit is obtained through a normally closed contact on *M* to energize the *CT* timing-delay coil and to charge capacitor *C1*. Contacts *CT1* and *CT2* on relay *CT* are open with the relay energized. Capacitor *C2* is charged through the normally closed contact on the 2A contactor. Pressing the "start" button energizes the main contactor *M*, which maintains itself through a normally open interlock finger. Relay *FA* is energized, and its contact *FA1* short-circuits the field rheostat. The motor accelerates from rest to a speed determined by the value of the *R1-R3* resistor. The circuit to timing relay *CT* is opened by the interlock on *M*, and capacitor *C1* discharges through the *CT* coil and the *AB* resistor. Contacts *CT1* and *CT2* can be individually adjusted to close at any time during the capacitor discharge period. Closing *CT1* energizes the 1A contactor, which short-circuits the *R1-R3* resistor. The motor then accelerates to a speed determined by the value of the *R2-R3* resistor step. Closing *CT2* energizes 2A and connects the motor across the line, permitting it to accelerate to normal speed.

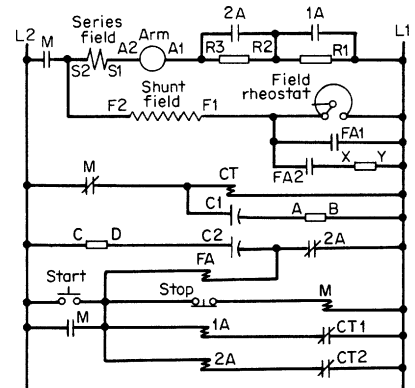


FIGURE 20-59 Time-limit acceleration with definite-time relay.

Relay *FA* is deenergized when 2*A* closes. Contacts *FA*1 and *FA*2 remain closed for a definite time because of the discharge of capacitor *C*2 through the *FA* relay coil. When contact *FA*1 opens, a resistance is inserted in the motor shunt field, equivalent to the field-rheostat resistance and *XY* resistance in parallel. Opening *FA*2 disconnects *XY*, and the motor runs at a speed determined by the setting of the field rheostat.

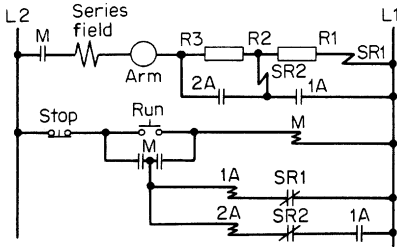


FIGURE 20-60 Direct-current series-relay accelerations.

Direct-current starters with current-limit acceleration are designed to half the starting operation whenever the required starting current exceeds an adjustable predetermined value, the starting operation being resumed when the current falls below this limit. With current-limit acceleration, the time required to accelerate will depend entirely upon the load. When the load is light, the motor will accelerate rapidly, and when it is heavy, the motor will require a longer time to accelerate. For this reason a current-limit starter is not so satisfactory as a time-limit starter for drives having varying loads. Time-limit starters are simpler in construction, accelerate a motor with lower current peaks, use less power during acceleration, and always accelerate the motor in the same time regardless of variations in load. Current-

limit starters are desirable for motors driving high-inertia loads. A typical current-limit starter is shown in Fig. 20-60. The relays *SR*1-*SR*2 have normally closed contacts connected in series with the coils of the accelerating contactors. The coils of these relays are connected in the main motor circuit. The relays are provided with an adjustment so they can be set to close on a selected value of current.

Pressing the “run” button energizes the main contactor *M*, which closes and connects the motor to the line in series with the *R*1-*R*3 resistor. Motor current will flow through the *SR*1 coil, and its contacts will open rapidly and prevent 1*A* from closing. When the motor has accelerated enough to bring the line current down to the value for which *SR*1 is set, the relay contacts will close; a circuit is then provided for 1*A*, which closes, cutting out the first step of resistance and short-circuiting the *SR*1 coil. Current now flows through the *SR*2 coil and the 1*A* contacts. *SR*2 relay contacts open and prevent 2*A* from being energized. The motor accelerates again, and when the current falls to the value for which *SR*2 is set, its contacts close, energizing 2*A* and connecting the motor across the line.

Magnetic controllers for large dc motors are manufactured in forms to suit the application. The controllers are available in the following forms: (1) nonreversing, without and with dynamic braking; (2) nonreversing with speed regulation by field control, without and with dynamic braking; and (3) reversing with dynamic braking, without and with speed regulation by field control.

20.9.3 Synchronous Motor Starting

Methods of Starting Synchronous Motors. The method used to start a synchronous motor depends upon two factors: the required torque to start the load and the maximum starting current permitted from the line. Basically, the motor is started by using the damper windings to develop asynchronous torque, or by using an auxiliary motor to bring the unloaded motor up to synchronous speed. Recently, solid-state frequency converters have been designed to bring up to speed large several-hundred-MVA synchronous motor/generators for pumped-storage plants.

Synchronous-motor starters of the full-voltage type connect the motor directly to the supply lines. The field winding is short-circuited through a discharge resistor during the starting period. The field is connected to the dc lines when the motor is at a speed near synchronism. Reduced-voltage starters connect the motor to a reduced voltage for starting and transfer to full voltage at a speed just below synchronism. This transfer may be controlled by a time relay or a frequency relay. The field is energized either immediately before or immediately after the full-voltage switch closes. Most modern synchronous motors obtain their field voltage from a brushless exciter on the shaft.

Figure 20-61 is a simplified diagram of a synchronous motor controller arranged for starting the motor directly across the line and synchronizing by a relay operating at a selected frequency. Pressing the start button energizes relay 1CR and contactor *M* to connect the motor stator windings to the ac lines. Current at line frequency is induced in the rotor field winding that flows through the discharge resistor *FD* and the coil of relay *FR*. A small portion of this current flows through the reactor *X*, but the amount is limited, as the frequency is high. Relay *FR* closes rapidly, and the contacts on *FR* open the circuit to the *FS* field contactor. As the motor accelerates, the frequency of the induced current in the field winding decreases and an increasing portion of the current flows through the reactor *X*. At a speed close to synchronism most of the current flows through *X*, and there will no longer be enough current flowing through the coil *FR* to keep the relay armature closed. Relay *FR* then opens, and the contacts on *FR* close to energize field contactor *FS*. Contactor *FS* connects the field to the dc lines and opens the field discharge circuit through resistor *FD*, and the motor pulls into synchronism.

Relay *FR* is polarized by a coil connected across the dc lines through interlock contacts *M_a*. Polarizing the synchronizing relay provides a means for energizing the field contactor at a point in the ac wave most favorable to synchronism. Brushless synchronous motors use electronic circuits on the rotating portion to control the switching time for the field.

Speed-Control Devices. Speed control of electric motors may be obtained by various means. The design of a speed-regulating controller is determined by the type of motor with which it will be used. Table 20-17 lists the various types of motor in general use and the corresponding type of speed control for each.

Multispeed squirrel-cage motors are suitable for applications that require up to four operating speeds but that do not require speed control between these fixed speeds. However, a solid-state inverter plus a single-speed motor might be less costly than a multispeed motor, and provide much more cost-efficient operation.

Controllers for multispeed ac squirrel-cage motors may be either the drum type or the magnetic type. Drum controllers are widely used, because the many changes in connections required to obtain different speeds can be readily accomplished. Drum controllers can be used with reconnected winding or separate-winding-type motors and with constant-torque, variable-torque, or constant-horsepower motors. Low-voltage and overload protection can be obtained by using a magnetic contactor and overload relay. When complete control by push buttons or other pilot devices is required, magnetic contactors are used to change the motor connections. Controllers of this type can be arranged to permit starting at any speed or to permit starting only at the slowest speed and changing to each higher speed in sequence.

Primary Voltage Control. AC squirrel-cage motors are inherently constant-speed motors when supplied directly from utility lines. Narrow-speed-range control is obtained by adjusting the primary voltage on Design D motors using saturable reactors or solid-state phase-controlled thyristors in the stator circuits. Wide-speed-range control is obtained by adjusting the primary frequency and voltage on Design B motors using motor-alternator sets or solid-state frequency converters. The frequency of 60-Hz motors is typically adjusted from 3 to 120 Hz. From 3 to 60 Hz, the voltage is raised proportional to frequency so that the motor can deliver its full rated and breakdown torque. From 60 to 120 Hz, the voltage is kept constant so that the motor can deliver its rated horsepower.

Speed is controlled with thyristors in each of the lines to the stator of the induction motor as shown in Fig. 20-62a. Retarding the firing angles of the thyristors reduces the stator voltage of the

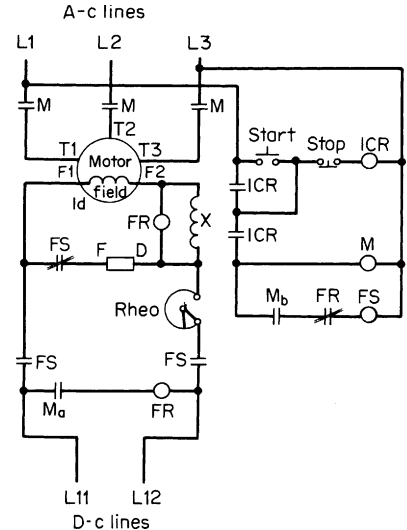
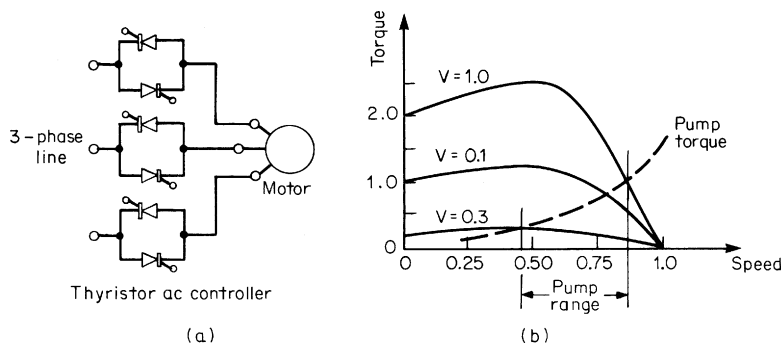


FIGURE 20-61 Full-voltage synchronous motor controller with synchronization based on frequency.

TABLE 20-17 Types of Motor Speed Control

Type of motor	Type of speed control	Speed-control range	Speed drops; no load to full load, % base speed
AC, squirrel	Multispeed Pole changing by multiple windings or reconnectable single winding	Up to 4 initial speeds	Up to 5% (slip)
	Solid-state primary voltage control	5 to 1	20%
	NEMA Design D motor Stator frequency control, constant V/Hz	20 to 1 at constant torque, plus 3 to 1 at constant hp	3%
	Solid-state inverter		
DC, shunt-wound	Stator frequency control	20 to 1 at constant torque, plus 3 to 1 at constant hp	Zero
	M-G set or solid-state frequency converter		
AC, slip-ring	Secondary resistors connected to slip rings	3 to 1	3%, full speed; 50%, minimum speed
	Pumpback of slip-ring power	20 to 1	3%
	M-G set or solid-state converter		
DC, shunt-wound	Adjustable armature voltage	20 to 1 at constant torque, plus 3 to 1 at constant hp	Up to 5%
	Solid-state converter or M-G set (Ward Leonard) plus field weakening		
DC, series-wound	Series resistors	20 to 1	Up to 100%
	Solid-state dc chopper	20 to 1	Up to 3%

**FIGURE 20-62** Primary-voltage control: (a) circuit of controller; (b) torque-speed characteristic at three-stator voltages; pump characteristic and range for 10% to 100% power.

motor. The torque at each speed is reduced as V_2 , as shown in Fig. 20-62*b*. NEMA Design D motors ensure a sufficient range of descending torque in which the motor can stably drive its load. The power loss in the rotor is proportional to the torque $\times$ slip. With pump and fan loads, as shown in Fig. 20-62*b*, the torque is reduced as speed, so that the rotor power loss is acceptable at reduced speed. Typical ranges of pump and fan operation are 50% to 100% speed, 10% to 100% power.

Other Speed-, Frequency-, or Voltage-Controlling Devices. Adjustable-frequency ac induction motor drives consist of a solid-state rectifier, a solid-state inverter, the motor, and necessary controls. As shown in Fig. 20-62*a*, the rectifier converts power at 60-Hz line frequency to dc power; the inverter converts dc power to power for the motor which is adjustable in frequency and voltage. Inverters are classified by their output; they include six-step voltage, current source, and pulse-width-modulated voltage. The six-step inverter in Fig. 20-63*a* causes the motor current to approximate a sine wave.

These ac drives operate in two modes with respect to base speed, as shown in Fig. 20-63*b*. From near zero to base speed, the inverter frequency and voltage are raised in proportion so that they both reach rated value for the motor at base speed. This is termed the *constant-torque mode* because the motor can deliver its rated torque anywhere in the speed ranges below base speed. From base speed to 200% or more of base speed, the inverter frequency is raised, but the voltage is maintained constant at the rated motor voltage. The consequence is that the magnetic field in the air gap of the motor decreases and the motor is able to deliver only $1/2$ times its rated torque. However, the product of torque and speed is constant; the operation is termed the *constant horsepower mode*. The maximum speed depends on the mechanical capability of the motor to run above base speed and the maximum design frequency for the inverter.

AC synchronous motors are speed-controlled in special applications where their self-excitation simplifies the frequency conversion equipment and where two or more motors must operate in synchronism with the supply. Adjustable-frequency, adjustable-voltage power is supplied from a motor-alternator set, or from a solid-state frequency converter. The solid-state converter is of the cycloconverter type for speeds up to 30% of the rated speed. For wide speed range, the frequency converter is a forced-commutated inverter or a load-commutated inverter, which relies on the self-excitation of the motor to commutate the thyristors.

Synchronous motors with permanent-magnet fields rated up to about 30 hp are used in textile applications, where multiple motors are operated in synchrony from a common power supply. Synchronous motors in the range of 750 to 5000 hp and larger are used for driving large blowers, boiler fans in power plants, large pumps, and other applications requiring large motors. The block diagram for a load-commutated inverter drive is shown in Fig. 20-64. The two converters are phase-controlled thyristor bridges which can rectify or invert power, as necessary. The thyristors in the inverter operate in the firing-angle range from 90° to less than 180° , and they are commutated by the voltage generated in the stator windings of the motor by the rotating field.

AC slip-ring motor control requires that power be extracted from the rotor windings via the slip rings to reduce the motor speed, that is, increase the slip. Three methods are used: (1) secondary resistors, (2) rotor-power recovery by auxiliary rotating machines, and (3) rotor-power recovery by auxiliary solid-state rectifier and converter. The auxiliary systems recover the electric energy that would be dissipated in the secondary resistors.

AC slip-ring motor secondary-resistor speed regulators consist of a contactor to connect the primary of the motor to the supply lines and some form of resistance-switching device for the secondary circuit. The switching device may be a three-arm faceplate controller, a drum, or magnetic contactors. Regulating devices differ from starting devices in that the switching means can remain continuously on any one of the resistor steps. The motor will therefore operate continuously at a reduced speed, as determined by the amount of resistance remaining in the motor circuit. The use of secondary resistance for speed control is not an efficient method because of the power loss in the resistor. The amount of speed reduction obtained will vary directly with the load on the motor. Speed controllers of this type are usually designed for 50% speed reduction. Under favorable conditions, however, motors can be operated at 75% speed reduction.

The resistors are of the same type as the resistors used for armature regulation of dc motors.

Rotor-power recovery drives are often classified as either constant horsepower or constant torque; the designation refers to the inherent limitation in power based on full current and flux in the main

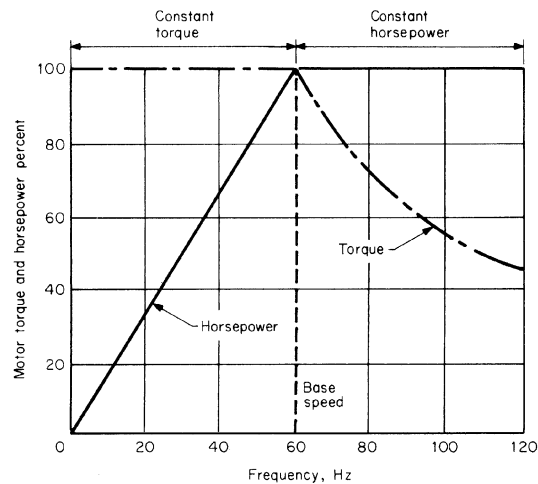
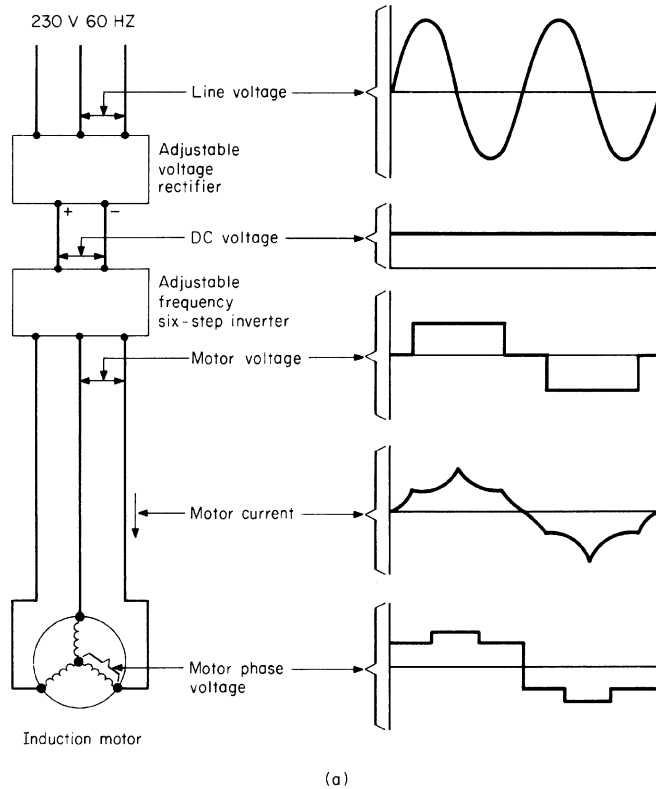


FIGURE 20-63 (a) Adjustable-frequency induction-motor drive using six-step inverter; (b) torque and horsepower capabilities of adjustable-speed drive below and above base speed.

machine. In the first scheme (constant-horsepower drive), the slip energy is converted into mechanical power and then returned to the main motor shaft. Since horsepower is a function of the product of torque and speed, such motors have high torque at low speeds and lower torque at higher speeds. In drives using this arrangement, the auxiliary machine is mounted on or mechanically geared to the main motor shaft (Fig. 20-65a).

In the second scheme (constant-torque drive), the slip energy is converted into electric power of the frequency and voltage of the supply circuit and is returned or fed back into the line. Since this power is not delivered to the main motor shaft, the auxiliary machine is not mechanically attached to the shaft but is separately driven. As the limiting torque of the main motor is constant, the maximum horsepower output is proportional to the operating speed (Fig. 20-65b).

The classical recovery systems using auxiliary machines are termed the *Scherbius drive* and the *Kr mer drive*. The former employs ac commutator machines; the latter relies on a dc link and rotary converters. A variation of the Kr mer drive uses a synchronous motor and a dc generator in place of the rotary converter and a constant-speed set feeding the slip power back into the line. This drive has been used for a number of large wind-tunnel drives. It is particularly adapted to a wide range of speed control and to minimum disturbance on starting.

In a solid-state version of the modified Kr mer drive, the slip-ring power is rectified in a diode bridge, then passed over a dc link to a line-commutated inverter that returns the power to the supply line. The drive operates with characteristics similar to the adjustable-armature-voltage dc system. The speed is controlled by the firing angle of the inverter. The recovery systems are economical for narrow speed ranges, such as for fans and pumps, or where the horsepower rating is so large that the costs of the controls are minimized.

DC solid-state adjustable-voltage control utilizes phase-controlled 1-phase or 3-phase thyristor bridge rectifiers to provide armature and field voltage to independent-field dc motors. A typical armature-voltage supply is shown in Fig. 20-66a. As the firing angles of the thyristors are adjusted from 90° to 0° , the dc armature voltage rises from zero to rated value, and the speed follows in proportion.

The speed-torque characteristics of the dc drive are shown in Fig. 20-66b. In the range from zero to base speed, the field current is at maximum, but the armature voltage is raised until it reaches rated value at base speed. At any one setting of armature voltage, the speed is relatively constant over the load torque range. The firing angles of the thyristor are adjusted by a regulator to maintain the speed constant at the set point. At any speed, the rated torque is available in this range. Above base speed, the armature voltage is held at rated, but the field current is reduced to obtain the higher value of speed. The maximum output of the motor is its rated horsepower in this range.

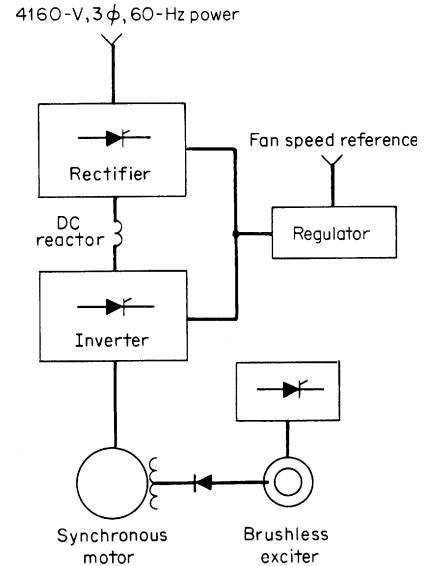


FIGURE 20-64 Block diagram of dual-converter synchronous-motor fan drive.

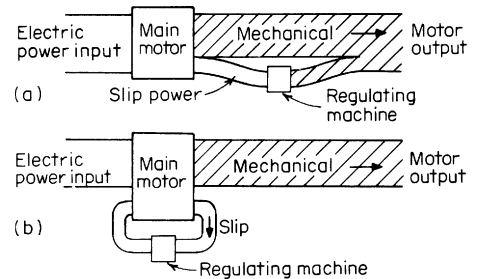
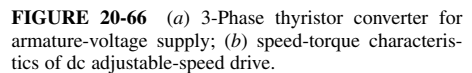


FIGURE 20-65 (a) Constant-horsepower drive; regulating machine, coupled to main motor, returns power mechanically; (b) constant-torque drive; regulating machine, mechanically separate from main motor, returns slip power electrically.

Armature-regulating and field-regulating resistors are used for the speed control of dc motors fed from fixed-voltage dc supplies as shown in Fig. 20-69. Armature-regulating resistors provide starting and speed-control duty in multiple steps, usually for fan loads. The resistors are usually designated for continuous duty, in accordance



with a NEMA classification number between 91 and 96, inclusive. The specific classification within this group is determined by the motor-starting current allowed, with all resistance in the circuit. The total ohms in the resistor are usually determined by the speed reduction required and the torque of the load. The IR drop across the resistor is the difference between the dc line voltage and the armature voltage, which is proportional to the speed. The current I is proportional to the torque. For example, at 50% speed a fan load requires 25% to 40% of its current at full speed. The total ohms are divided into steps to give equal speed changes per step.

Field-regulating resistors should be designed on the basis of actual test data on the motor with which the control is to be used. The motor manufacturer will supply such data as the resistance of the shunt field or the maximum field amperes, the required rheostat resistance or the minimum field amperes. The total ohms in the rheostat will therefore be determined by the motor data. The number of steps in the rheostat must be large enough to limit the speed increase per step to an acceptable value. The character of the resistor material used may require a large number of steps, in order to keep the wattage per step on the rheostat within limits. The number of steps must be sufficiently large to keep the voltage drop at any step within specified limits to prevent arcing on the contacts. The arcing limits for sliding contacts vary from 200 V at 0.4 A to 50 V at 1 A and 25 V at 4 A. This voltage is the product of the step ohms and the amperes flowing before the step is inserted. The amount of resistor material required in the field rheostat is determined by the wattage which must be dissipated. Each step must be designed on the basis of the maximum current which it will have to carry. The total wattage capacity of the rheostat will be the summation of the step wattage. The distribution of the resistor between the various steps can be determined on the basis of obtaining either equal speed changes per step or equal percentage speed changes per step. Common practice at present is to provide equal speed changes per step, and a speed reduction to 20% of what is rated can be obtained with armature-regulating resistors. A speed increase up to 200% can be obtained by field resistors with a properly designed motor.

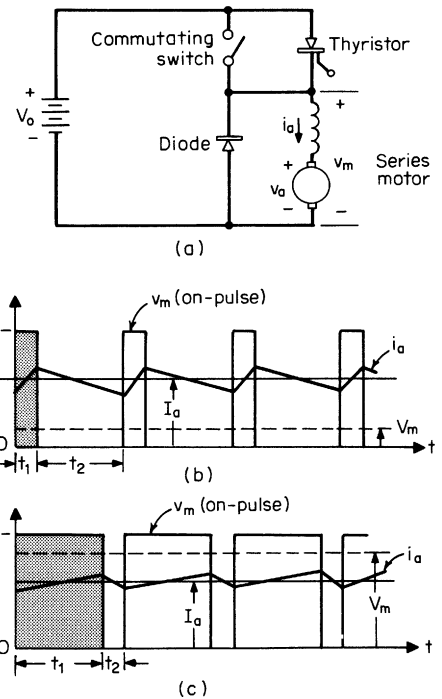


FIGURE 20-68 Chopper speed control for series motor: (a) circuit; (b) waveforms at low speed; (c) waveforms at high speed.

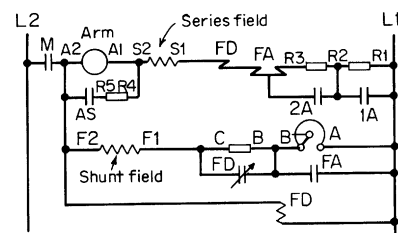


FIGURE 20-69 Armature speed-control resistors $R1-R2$ and $R2-R3$. Field speed-control resistors $A-B$ and $B-C$.

20.10 STOPPING DEVICES

Electric braking is used when the dc or ac motor is allowed to make several revolutions before coming to rest. In electric dynamic braking, the kinetic energy of the motor and the load is absorbed in the resistance of the motor windings, or in a resistor switched into the circuit. In electric regenerative braking, the energy is returned to the supply line. Magnetic brakes are used to obtain quick, accurate stopping

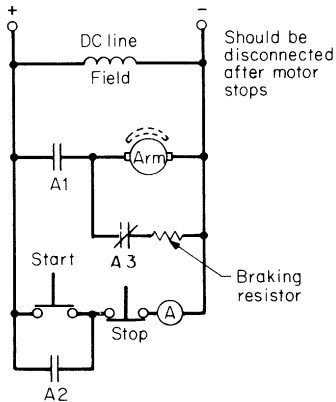


FIGURE 20-70 Dynamic braking circuit for shunt-wound dc motor.

speed range by field. The braking obtained decreases as the motor speed is reduced. The final stopping of the motor is due to friction, since at standstill no braking torque is obtained. For very quick stopping the braking resistance can be reduced in several steps as the speed decreases, thereby keeping the current at a high value. This type of braking is effective where it is necessary to stop a motor quickly. Mechanical brakes must be used to hold a load at a standstill.

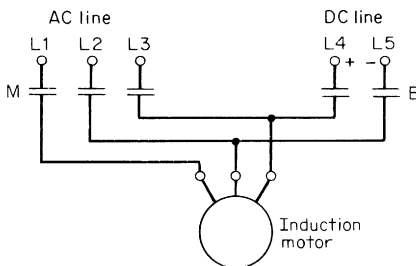


FIGURE 20-71 Dynamic braking circuit for 3-phase induction motor. Contacts *M* are for line-starting the motor. Contacts *B* are for applying direct current for braking.

voltage and I = normal current. The plugging resistance is determined by subtracting the armature resistance from R_t .

Plugging is used with *ac motors* to obtain a very quick stop. Three-phase squirrel-cage and wound-rotor motors may be plugged by reversing the line connections to any two of the stator terminals while the motor is running in the forward direction. In order to use plugging as a stopping means, a zero-speed switch is necessary to open the reverse contactor and prevent reversing the motor. A common form of zero-speed switch is the friction type, in which a contact is held closely by the friction of a small belt over a pulley driven by the motor. Any slight reversal of the motor will cause the contacts to open. Another type of zero-speed switch uses a disk which rotates in the magnetic field produced by Alnico magnets. Eddy currents are induced in the driven disk, and the magnetic reaction turns the magnet assembly to close the contacts. The contacts can be adjusted to open when the motor is near zero speed.

An electrical plugging relay is also used which remains closed until the line current decreases to the normal inrush current corresponding to the starting condition, or zero speed on the motor. This device has the advantage of not requiring a mechanical connection to the motor or machine.

and to hold the load after stopping. Most brakes are spring-set and electrically released, so that braking will be obtained even though an electrical failure occurs.

Dynamic braking of a dc shunt-wound motor can be obtained by disconnecting the motor from the line and shunting the armature with a resistor. As shown in Fig. 20-70, when the motor is running, contacts A1 and A2 are closed, and A3 is open. When the stop button is pressed, contact A1 opens to disconnect the armature from the line; holding contact A2 opens; and contact A3 closes to put the braking resistor across the armature terminals. The field must remain connected to the line during braking. For constant-speed motors, the ohmic value of the braking resistor is $R = (E - I_a R_a) / I$. The value of I determines the amount of braking obtained and may vary from 150% to 300% of normal current. With shunt motors, having speed regulation by shunt-field control, the general practice is to strengthen the field during braking by short-circuiting the field rheostat. When this is done, the ohms in the braking resistor should be $R = (E - I_a R_a) / I \times$

Dynamic braking with an ac induction motor can be obtained by disconnecting the motor from the power supply and applying direct current to one of the stator phases. As shown in Fig. 20-71, the kinetic energy of the rotor and the load is dissipated in the rotor circuit resistance.

Plugging is used with *dc motors* to obtain very rapid reversing and is accomplished by connecting the motor to the line in the reverse direction while it is still rotating in the forward direction. The countervoltage of the armature is added to line voltage to force current through the armature and series resistor. The total resistance in circuit for plugging should be $R_t = 2(E - I_a R_a) / \text{inrush current}$. With the armature drop assumed as 10%, the formula may be written $R_t = 1.8E / 1.5I = 1.2E / I$, where E = line

Regenerative braking is used with dc adjustable-armature-voltage controllers to obtain rapid stopping. For a solid-state armature converter, either the dc motor field current is reversed to reverse the armature voltage, or a second reverse polarity converter is switched in. In the first case, the direction of the armature current remains the same, but the armature voltage reverses. In the second case, the direction of the armature current reverses, but the armature voltage remains the same. The regulator controls the firing angles of the converters to maintain prescribed armature current during the braking period. For an ac-motor-driven dc generator supplying the dc motor in a Ward Leonard system, the generator voltage exceeds the countervoltage of the driven motor, and power is taken from the ac lines to keep the driven machine rotating. If the field strength of the generator is decreased, the generator voltage becomes less than the countervoltage of the motor and the motor feeds power back to the generator and to the ac lines. When the countervoltage exceeds the generator voltage, a heavy reverse current is obtained, as the value of this current is limited only by the low resistance of the loop circuit. A very rapid stop is obtained, since the voltage across the generator field can be reduced to zero in about 3 s.

Direct-current brakes are set by a spring and are released by means of a solenoid or a direct-operating magnet. The coil in the operating device may be for either series or shunt connection and for continuous or intermittent duty. Series-wound brakes are operated by motor current and require 80% full motor current to release with a continuous-duty coil and about 40% full-load current with an intermittent-duty coil. The brake will be held released on about 10% full-load motor current. Intermittent-duty series brakes are rated as either $\frac{1}{2}$ -h duty or 1-h duty, to correspond to the rating of intermittent-duty series motors. A series-brake coil will carry full motor current continuously, for a period corresponding to its rating, without exceeding a temperature rise of 75°C. Shunt brakes may be for either continuous or intermittent duty. Intermittent duty is defined as 1 min on and 1 min off or the equivalent, the longest time on not to exceed 1 h. Shunt brakes will release at 80% of normal voltage, when adjusted for rated torque. The larger-sized brakes use partial-voltage coils and protecting resistors. Series brakes have a heavy wire coil, which is less likely to give trouble, are faster in operation, and will set whenever the armature circuit is open. Data on a line of dc magnet-operated shoe brakes are given in Table 20-18.

Alternating-current brakes have three forms of operating mechanism: solenoid type, torque-motor type, and thruster type. The smaller sizes of brakes are usually made in the solenoid type. On the larger sizes, a vertically mounted torque motor and antifriction ball jack provide a quiet, low-inrush-current operating means. On application of power to the motor, the rotary motion of the armature is transformed into straight-line motion through the antifriction jack. With the brake fully released, the torque motor is stalled across the line. When the motor is disconnected from the line, the spring in the brake overhauls the motor mechanism and applies the brake. Data on a line of brakes of this type are given in Table 20-19.

The thruster-type operating mechanism consists of a self-contained motor-driven centrifugal pump, oil chamber, and a piston which produces a straight-line movement to release the brake.

The *brake size* for most applications can be determined by using the formula $T = 5252 \times \text{hp}/r/\text{min}$, where T = full-load motor torque in pound-feet, hp = motor horsepower, r/min = speed of shaft on which brake wheel is mounted. A brake should be selected with a torque rating equal to or greater than the full-load motor torque T . In some cases, the braking torque is determined by extreme operating conditions against which the brake must hold, for example, heavy ice loads on bascule bridges or conditions

TABLE 20-18 Direct-Current Magnet-Operated Shoe Brakes

Wheel diameter, in	Maximum torque, lb · ft			
	Shunt-wound		Series-wound	
	Int. duty	Cont. duty	$\frac{1}{2}$ -h duty	1-h duty
8	100	75	100	65
10	200	150	200	130
13	550	400	550	365
16	1000	750	1000	650
19	2000	1500	2000	1300
23	4000	3000	4000	2600

Note: Int. = intermittent; Cont. = continuous; 1 in = 25.4 mm; 1 lb · ft = 1.356 N · m.

TABLE 20-19 Alternating-Current Torque-Motor-Operated Brakes

Wheel diameter, in	Maximum torque, lb · ft		Voltamperes		WR ² of wheel	Safe maximum rpm	Weight of brake, lb
	Int. duty	Cont. duty	Int. duty	Cont. duty			
10	160	125	160	105	3.1	2015	150
13	400	325	210	140	12	1550	240
16	800	600	300	240	25	1260	370
20	1600	1200	1000	470	75	1012	750
25	3200	2400	1500	550	220	806	1210

Note: 1 in = 25.4 mm; 1 lb = 0.4536 kg; 1 lb · ft = 1.356 N · m.

of unbalance on skip hoists. In these cases, the maximum load must be calculated and translated into pound-feet torque at the shaft on which the brake is mounted. Sufficient lining area is provided on all sizes of brake for the average application. However, a careful check as to lining area must be made when brakes are used for frequent stopping or for stopping high-inertia loads.

20.11 MOTOR-PROTECTING DEVICES

Fuses should be provided for motor circuits, in accordance with the NEC. The current rating of the fuse must be considerably higher than the current rating of the motor, or the fuse will blow when the motor is started. For that reason fuses do not provide adequate overload protection. They furnish protection for the motor only in case of a short circuit or a very heavy overload. Their primary purpose is to protect the circuit rather than the motor.

Magnetic-type overload relays are operated by direct magnetic action of the motor current on a plunger. The relay consists of a series coil connected in the motor circuit and a plunger which is pulled up into the center of the coil when a certain value of current has been reached. When the plunger is lifted, a contact is tripped, opening the motor contactor-coil circuit and disconnecting the motor from the line. The tripping current can be varied by adjusting the initial position of the plunger with respect to the coil. Time delay in tripping is obtained by attaching a small oil dashpot to the plunger. The time delay can be adjusted so that the overload will not trip on the starting-current inrush but will trip on small sustained overloads.

Thermal overload relays are available in the bimetallic type and the fusible-alloy type. The bimetallic type has two heaters in series with the circuit to be protected, and above these heaters are two strips of bimetallic material, which act as latches for the contact members. Bending of the bimetallic strips under heating of overload current will release the latches and allow the contacts to open. The fusible-alloy type has two heaters, each surrounding a thermal element consisting of a small tube, inside which is a loose-fitting shaft. The tube and shaft are rigidly joined by a special low-melting eutectic alloy. On overload, the increased current drawn melts the alloy, allowing the shaft to turn and the contacts to open.

Characteristics of a typical thermal overload are shown in Fig. 20-72. An inspection of these curves shows that the thermal overload adequately protects the wiring, that the fuse blows first on short-circuit current, and that the thermal relay allows the motor ample time to accelerate. A thermal overload has a

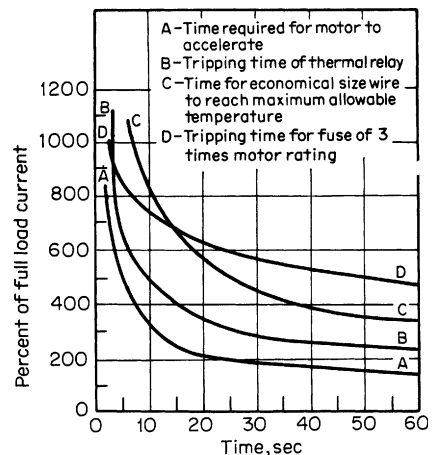


FIGURE 20-72 Characteristics of thermal overload relays.

tripping characteristic which corresponds closely to the heating characteristics of a motor and, therefore, provides an ideal protecting means. An overload coil should be selected so that the maximum permissible output can be obtained from the motor. A motor rated 40°C rise on the basis of 40°C ambient temperature will have a final safe temperature of approximately 95°C and will operate at 15% overload continuously without overheating. An overload coil should therefore be selected having an ultimate tripping current equivalent to 15% overload on the motor. A continuous overload of 15% would therefore ultimately trip the thermal relay. For overloads in excess of 15%, the tripping time would be shorter than the time required for the motor to reach a dangerous temperature.

Low-voltage protection is the effect of a device, operative on the reduction or failure of voltage, to cause and maintain the interruption of power to the main circuit.

With magnetic controllers, this protection is obtained by using some form of 3-wire master switch. Should the line voltage drop to a low value or fail altogether, the main-line contactor will open and remain open, stopping the motor. To restart, it is necessary to push the “start” button. This type of control should always be used where the unexpected restarting of a motor after voltage failure may be dangerous to workers or equipment.

Low-voltage release is the effect of a device, operative on the reduction or failure of voltage, to cause the interruption of power to the main circuit but not to prevent the reestablishment of the main circuit on return of voltage. Such protection is obtained when a 2-wire pilot device, for example, a snap switch, float switch, or pressure switch, is used.

Phase-failure protection is the effect of a device, operative upon the failure of power in one wire of a polyphase circuit, to cause and maintain the interruption of power in all the wires of the circuit.

Phase-reversal protection is the effect of a device, operative on the reversal of the phase rotation in a polyphase circuit, to cause and maintain the interruption of power in all wires of the circuit. Protection of this type is necessary on elevators, where reversing of the phases would cause the car to start in a direction opposite to that in which the operator expects it to move.

Field-failure protection is usually provided in controllers for dc shunt- and compound-wound motors. The coil of a relay is connected in series with the motor shunt field, and a normally open contact of the relay is connected in the stop circuit. If the field circuit is opened, the relay will be deenergized and the motor will be disconnected from the line. This prevents overspeeding the motor owing to an open circuit in the field. A *field protective relay* is used to insert resistance in series with the shunt field whenever the motor is not running. The coil of the relay is connected in parallel with the main switch coil, and a normally open relay contact is used to short-circuit a step of resistor in the field circuit. The resistor should be designed to reduce the voltage across the field to one-half line voltage. This reduces the field wattage to one-fourth the normal value and prevents overheating the field with the motor at standstill.

A *field-discharge resistor* should be provided for 230-V motors rated 7½ hp or more and for 550-V motors rated 5 hp or more whenever the shunt-field circuit must be opened. The ohmic value of a discharge resistor should be 1 to 3 times the ohms in the field. If a resistance of three times the field ohms is used, the induced voltage, when the circuit is opened, will be 4 times normal line voltage. This voltage, caused by the inductance of the field, must be limited to prevent damage to the insulation of the field windings. On nonreversing controllers without dynamic braking, the shunt field can be connected behind the main contactor and the field allowed to discharge through the motor armature.

20.12 AC DRIVES

General Theory of AC Drives. There are three basic types of ac machine—synchronous machines, wound-rotor induction machines, and squirrel-cage induction machines (see Table 20-20). Each of these machines is normally applied to a fixed-speed application. The speed of each is determined by the internal mechanical and electrical configuration. It can be displayed as

$$\text{Speed (r/min)} = \frac{120 \times \text{frequency (Hz)}}{\text{No. of poles}}$$

TABLE 20-20 Basic Types of AC Machine

Drive system	LCI-fed synchronous motor	LCI-fed squirrel-cage induction motor	Voltage-source PWM inverter-fed squirrel-cage induction motor	Wound-rotor induction motor with slip-recovery converter
System one-line diagram				
Type of machine	Synchronous motor	Squirrel-cage induction motor	Squirrel-cage induction motor	Wound rotor induction motor
Typical power range	1000–100,000 hp	1000–20,000 hp	1000–10,000 hp	1000–20,000 hp
Maximum speed	7500 rpm (depending on power)	7500 rpm (depending on power)	7500 rpm (depending on power)	1800 rpm
Typical speed range	10–100%	50–100%	0–100%	50–98%
Significant properties and features	Simplest converter Single-motor drive Four-quadrant operation	Applicable to existing SCIMs Nearly sinusoidal motor voltage and current	High-power factor Good dynamic performance over entire speed range Low harmonic distortion	Suitable for retrofit to existing slip-ring motor Very economical for narrow speed ranges Inherent bypass capability

Except for special cases, the number of poles in a machine is fixed and the incoming line frequency is normally fixed. Therefore, except for slip in induction machines, a given ac motor operated on a given electrical network will operate at a single fixed speed.

If the line frequency supplying the motor can be adjusted, then the speed of the motor can also be adjusted. That is the basis for adjustable-speed drives for ac motors.

Application and Economics of Speed Control. As previously noted, ac motors provide the motive power for a wide array of industrial applications. Most of these involve a centrifugal type of load, for example, fans, blowers, compressors, or pumps. The configuration of these devices is such that the *torque* required to turn them is proportional to the square of the speed. And the *power* required to turn them is proportional to the *cube* of the speed. The relationships

$$\text{Torque} \propto (\text{r/min})^2$$

$$\text{Power} \propto (\text{r/min})^3$$

is what makes adjustable-speed drives (ASDs) economically attractive.

Most of these devices are part of a process that requires some degree of flow or pressure control. This is normally performed via mechanical throttling of the flow, for example, inlet or outlet dampers, guide vanes, valves, or bypass systems. The net result of any of these methods is the consumption of excess energy required to overcome the pressure drop or bypass flow each creates.

However, efficient and precise control of the flow or pressure in a system can be obtained by directly controlling the speed of the device. This direct-speed control, coupled with the speed/power and speed/torque relationships shown above, results in an exceptionally efficient method of controlling the process. Several programs are commercially available to calculate energy savings and pay-backs based on energy rates, operating profiles, internal rates of return, etc.

Power Semiconductor Devices. In order to supply an adjustable frequency to an ac motor, the incoming constant-frequency voltage or current must first be *rectified* to a dc current or voltage. This dc voltage or current is then *inverted* to an adjustable frequency output. This is accomplished by power semiconductor devices.

These devices allow current to flow in only one direction. They act as electronic switches. Various types can be fired on and off at certain times in the cycle. This selected firing allows control of the resultant voltage or current.

Power electronic devices come in three basic types (Fig. 20-73):

Diodes. This is an uncontrolled device, that is, current can flow only in one direction. However, there is no gate to control the firing angle.

Thyristors. These devices also allow current to flow in only one direction. However, they include a gate circuit to delay firing until a given angle in the sine wave. This allows control of the resultant output dc current. However, it normally is turned off or *commutated* only when the voltage across it drops to zero.

Gate turnoff (GTO) thyristors. These are similar to basic thyristors. They also include a turnoff gate that allows the current to be blocked at any point in the cycle.

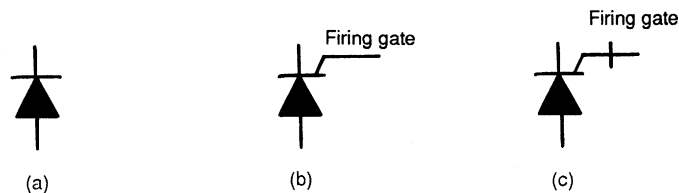


FIGURE 20-73 Main power electronic device used in modern frequency converters: (a) diode; (b) thyristor; (c) gate turnoff (GTO) thyristor.

AC Drive Systems. Electronic speed control offers much more than just energy savings. Reduced maintenance and reduced mechanical and thermal stresses are just a few of the advantages that can be realized.

The key to maximizing the many advantages of adjustable speed drives is applying the proper type of drive system. Following is an overview of the most important types of drive systems available today.

Most drive systems are composed of three major components—the input transformer, the frequency converter, and the ac machine. Additional components may include dc link reactors, harmonic filters, output filters, switchgear, etc. The requirements for these components will depend on the type of drive, user specifications, and vendor recommendation.

Connection to the Electrical Network. Most types of drive systems are connected to the electrical network through an input transformer (Fig. 20-74). This transformer serves many purposes. It transforms the network voltage to the optimal voltage for the frequency converter. It effectively lowers the short-circuit capacity seen by the drive to reduce “line notching” that can occur when thyristors commute from one phase to another. It also provides impedance in the line to reduce distortion. A line reactor can be used if the line voltage and converter voltage match. However, a three-winding transformer can be used to dramatically reduce harmonic distortion. The two secondary windings are phase-shifted 30 electrical degrees by connecting one in a delta configuration and one in a wye configuration. This effectively eliminates fifth and seventh harmonics and their multiples.

LCI/Synchronous Motor Drives. In this system, the line-commutated rectifier acts with the dc link smoothing reactor as a dc current source. The load-commutated inverter operates with the synchronous machine’s voltage and frequency to switch the dc current to the windings. The synchronous machine behaves like a dc machine with the inverter operating as a static commutator.

The load-commutated inverter (LCI) (Fig. 20-75) is the simplest type of frequency converter. Because the rectifier thyristors are commutated by the line voltage and frequency, and the inverter thyristors are commutated by the synchronous machine voltage and frequency, no special circuits are needed to accomplish commutation.

This type of drive has the added inherent advantage of 4-quadrant operation. Therefore, it is suitable for drives which may require regenerative braking or operation in both the motoring and generating modes.

LCI/Induction Motor Drives. An induction motor can also be driven with an LCI-type drive (Fig. 20-76). However, because of the inherent characteristics of an induction machine, the thyristors in the inverter section cannot be self-commutated by the motor voltage until it reaches approximately 50% speed. Therefore, additional circuitry must be added across the inverter or across the individual thyristors to force the voltage to zero and turn off the thyristors. Additionally, a filter on the output of the inverter is normally required to produce a sinusoidal current form to the motor.

This type of drive is commonly used as a retrofit to existing squirrel-cage induction motors. However, care should be exercised on such applications. All frequency converters impose additional losses and, therefore, additional heating on motors. Higher stresses are also placed on the insulation

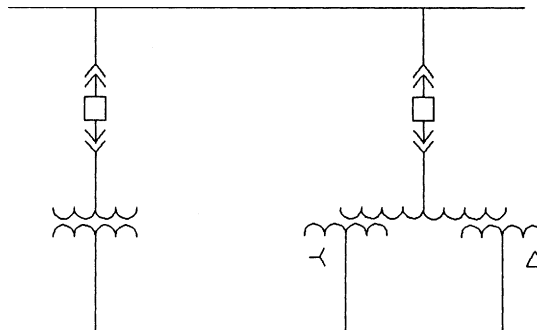


FIGURE 20-74 Two- and three-winding transformers.

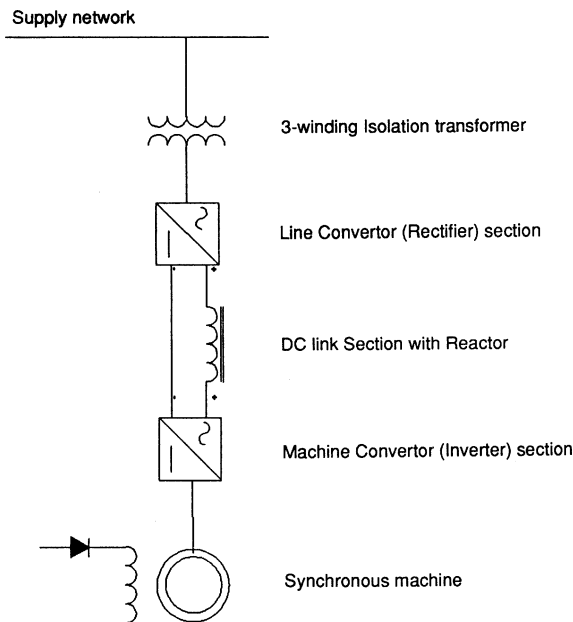


FIGURE 20-75 Basic LCI system design.

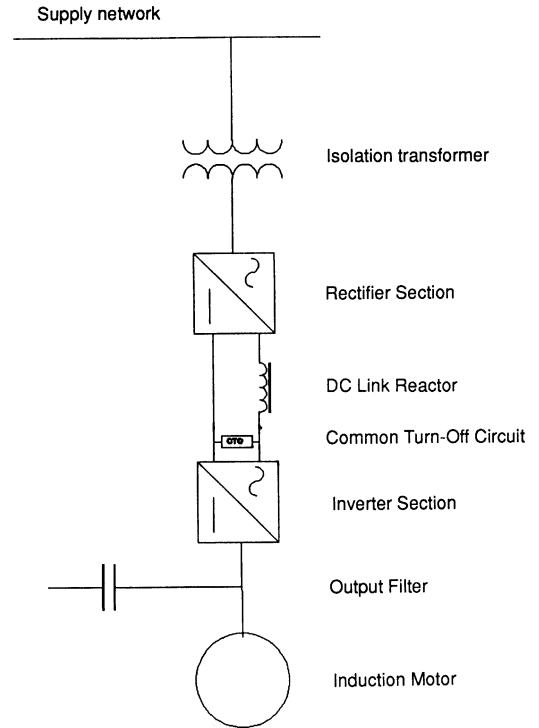


FIGURE 20-76 LCI drive with induction motor.

of the motor windings due to the distortion of the inverter's output waveform.

PWM/Induction Motor Drives. With the advent of high-power GTO thyristors, pulse-width modulated (PWM) frequency converters for powers up to 10,000 hp are now available. These can be supplied as either voltage-source (Fig. 20-77) or current-source configurations. For either configuration, the ability to *turn off* the device via a gate pulse eliminates a number of components in the power circuit.

The voltage source drive in particular has a number of benefits. The uncontrolled diode rectifier section results in a high line-side power factor (near unity) throughout the speed range. The distortion seen by the electrical network is also reduced since diodes always have an effective firing angle of zero. The PWM voltage-source output of the inverter produces a near-sinusoidal current in the motor. High dynamic performance can also be realized. Full torque can be maintained and controlled throughout the speed range—even at zero speed.

A unique application of voltage-source PWM drives is their use on coordinated sectional drive systems. Because the voltage in the dc link is maintained at a constant value, several inverter sections can be connected to the same rectifier/dc link section. This can result in significant savings in money and in space.

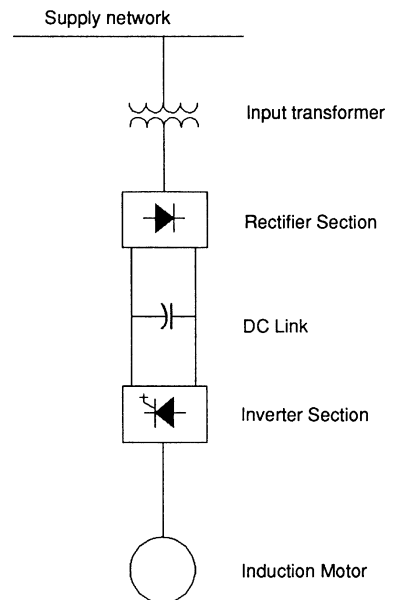


FIGURE 20-77 Voltage-source PWM inverter drive.

Slip Recovery (Cascade) Drives. A much different solution is a slip recovery, or cascade, drive system (Fig. 20-78). While the previously described systems vary the voltage and the frequency applied to the stator of the ac machine, a cascade drive is connected in the rotor circuit of a wound-rotor motor. Wound-rotor or slip-ring motors can be speed-controlled by connecting an external resistor to the rotor circuit via the slip rings. Since the slip (and hence the speed) of an induction motor is directly proportional to the losses in the rotor, increasing or decreasing the external resistance could vary the speed over a limited range. Historically, the resistance was adjusted via a liquid rheostat for stepless control, or a grid resistor for several steps in resistance. This method was also commonly used for starting of high inertia loads. The motor's starting torque and current characteristics could be adjusted during starting. Once it reaches rated speed, the slip rings are short-circuited and the motor functions as a squirrel-cage induction motor.

The cascade drive controls the speed in a similar fashion. However, as its name implies, rather than dissipating the energy across external resistors, it *recovers the slip energy* and returns it to the electrical network. This is realized by converting the low-frequency rotor current into line-frequency current. It is then transformed to the supply voltage via a feedback transformer. Starting is normally accomplished via conventional means with a liquid or grid resistor.

The cascade drive is an excellent solution when the speed range is relatively narrow—normally 50% to 70% to 100%. Because the converter handles only the *slip* power, it is much smaller than other types of frequency converters. As an example, if the desired speed range is 70% to 100%, the converter must be sized to handle only 30% of the rated power. This results in a very economical solution.

An additional advantage of this type of drive is that a bypass arrangement is inherent in the design. The normal starting sequence is to bypass the drive and connect it once the motor reaches a minimum control speed. Therefore, if the drive malfunctions for any reason, it can be bypassed and isolated. In this way repair can be accomplished without shutting down the process.

Other Drive Types. There are other types of ac drive systems used for specialized applications. One of these is the *cycloconverter* drive. This drive is normally applied to low-speed, high-torque, high-performance applications. These include metal rolling mills, large grinding mills for ore or in

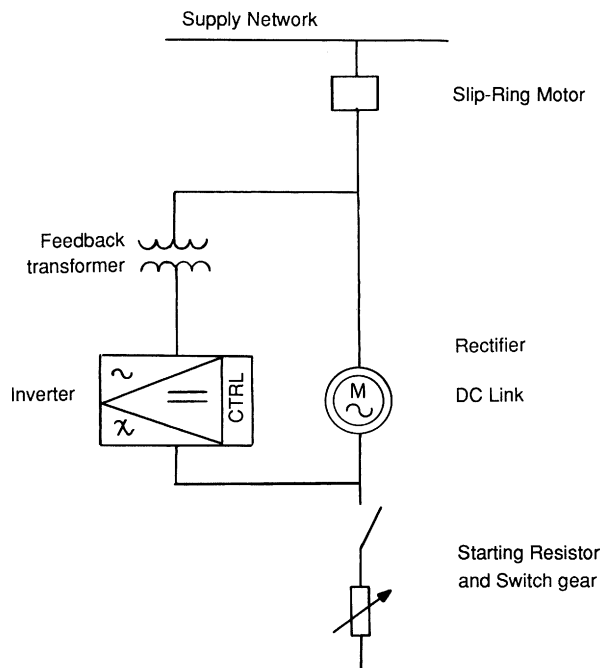


FIGURE 20-78 Slip recovery (cascade) drive.

cement applications, and ship propulsion. All these applications require precise speed and torque control to optimize the process.

The cycloconverter is effectively a separate frequency converter on each phase of a synchronous or induction motor. This allows for a more precise fabrication of the voltage waveform to the motor. This, in turn, results in a current wave shape that very closely approximates a sine wave. Consequently, the torque produced by the motor is very smooth throughout the speed range.

The design of the cycloconverter is such that its output frequency cannot exceed one-third of the line supply frequency. So, for a 60-Hz system, the maximum output frequency is 20 Hz. A 12-pole motor, which would normally have a synchronous speed of 600 r/min on a 60-Hz system, cannot be run up to only 200 r/min with a cycloconverter drive.

Another type of relatively exotic drive is the supersynchronous converter cascade. This is used for matching frequencies from a variable-frequency generator, for example, a hydropower station with varying head and speed.

Harmonic Impact of Drives on Electrical Networks. All drives result in some harmonic distortion in the electrical network to which it is connected. This is due to the fact that the power semiconductor devices “chop up” the incoming sine wave and reconstruct it at another frequency. By definition, this chopping up of the waveform results in distortion from a pure sine wave.

Harmonic distortion can have effects in several areas. Electronic equipment, such as computers, can malfunction due to changes in zero-crossing points in the supply waveshape. Motors may run hotter due to harmonic currents.

Many factors affect the magnitude of the distortion. The type of rectifier section on the drive has a major effect. Uncontrolled diode bridges will typically produce less distortion. Thyristor rectifier bridges will be somewhat higher since the firing angle is greater than zero.

The short-circuit capacity of the system at the point of connection is the major factor in determining distortion. The distortion can be estimated from Fig. 20-79. These curves clearly indicate that if the drive is connected to a relatively strong system, that is, one whose short-circuit capacity (SCC) is substantially higher than the converter rating, the total harmonic distortion seen by the network may not exceed the limits established by IEEE 519.

Connecting to the network with a 12-pulse configuration (through a 3-winding transformer) has a great impact on the distortion. The connection effectively eliminates the fifth and seventh harmonics and all multiples of them. Since the magnitude of the harmonic is inversely proportional to the order number, these are the greatest contributors to distortion.

If multiple drives are connected to the same bus, distortion can be further minimized by phase shifting the primaries of the drives to effectively create a 24-pulse connection. This is only feasible with drives utilizing a diode rectifier. This is due to problems with timing of the device firing on thyristor-type rectifiers.

If the type and configuration of the drive do not limit the harmonic distortion to an acceptable level, filters can be installed on the bus to further reduce their effect. These filters are configured with reactors, capacitors, and resistors to “trap” the unwanted harmonics. Typically they are “tuned” to a specific order number, that is, normally there are fifth, seventh, and eleventh harmonic filters. These filters need to be properly coordinated with the drive supplier and the electrical network to ensure that resonances are not created that could interact with other equipment.

Impact of Drives on Mechanical Systems. Careful consideration should be given to the *mechanical* system when applying a drive. One key point may be the natural critical speed or resonance point of the motor. When applied as a constant-speed machine, the motor may operate above or below its natural frequency with little problem. However, if the critical speed is within the desired speed control range, problems can occur. These can be addressed in several ways. Critical speeds can be changed somewhat via bearing or base configurations. Or, the drive can be programmed to avoid certain frequency or speed bands. In this case, the drive will quickly accelerate or decelerate the motor through the resonance points to minimize potential problems.

Just as the electrical network sees distortion from a drive, the connected load (normally a motor) also sees an imperfect sine wave as the output of the drive. This distortion of the incoming current

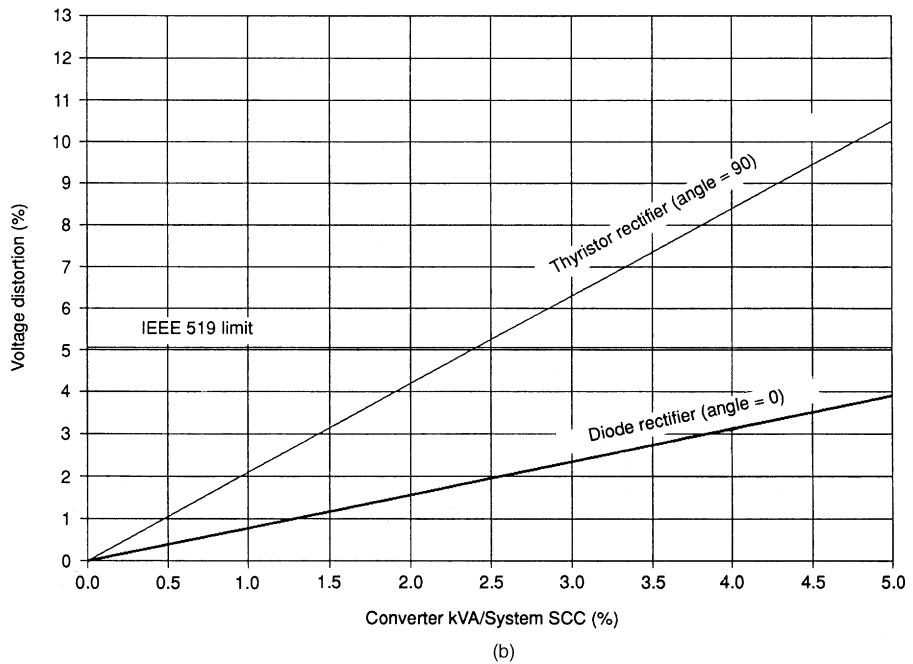
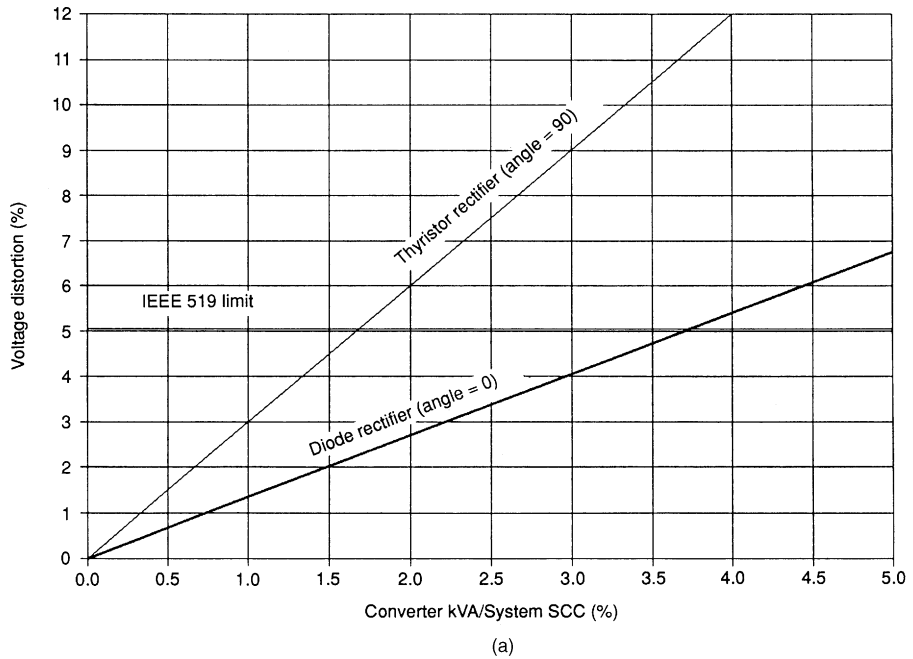


FIGURE 20-79 Harmonic distortion: (a) 6-pulse rectifier; (b) 12-pulse rectifier.

or voltage is translated into a distortion of the motor torque. This can be realized as torque pulsations at the motor shaft output. For many applications, this does not present a problem. However, for all applications, a detailed torsional analysis of the complete mechanical system should be performed to ensure that the drive will not excite any torsional resonance points. If such problems are uncovered early, they can usually be easily addressed through modifications to the drive or through a flexible type of coupling to dampen the torsional vibrations. The system torsional analysis may be performed by the drive vendor, the driven equipment vendor, or both.

Summary. Properly applied, ac drive systems can have tremendous positive impact on a wide range of processes and applications. Carefully engineered drive systems can provide many years of trouble-free operation.

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